FINAL REPORT

Demonstration and Verification of a Turbine Power Generation System Utilizing Renewable Fuel: Landfill Gas

ESTCP Project EW-200823

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14. ABSTRACT
This technology demonstration was funded under the US DOD ESTCP program and executed at the Ft. Benning Army Base. The objective of this demonstration is to provide a credible, independent, third party evaluation of the performance, economics and environmental impacts of the Ener-Core Powerstation™ (FP250) technology in a landfill gas (LFG) energy recovery application at a DoD site. The evaluation was designed to provide sufficient data to allow end-users, purchasers, and others to determine the feasibility of the technology at DoD sites and other applications. Success factors that were validated during this demonstration include energy production, emissions and emission reductions compared to alternative systems, economics, and operability, including reliability and availability.

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Table of Contents

List of Figures

List of Tables

Appendices

Acronyms

Acronym	Definition
ADQ	Audit of data quality
AEWRS	Army Energy and Water Reporting System
AIRR	Adjusted Internal Rate of Return
ANSI	American National Standards Institute
AQMD	Air quality Management Division
BLCC	Building Life-Cycle Cost
BTU	British thermal units (energy, usually thermal or chemical)
BTU/h	British thermal units per hour (rate of energy transfer or use)
CARB	California Air Resource Board
CO	Carbon Monoxide
CO_2, CO_{2e}	Carbon Dioxide, Carbon Dioxide Equivalent
DASA E&S	Deputy Assistant Secretary of the Army for Energy & Sustainability
dBA	Decibel, A weighting
DG	Distributed Generation
DNR	Department of Natural Resources
DoD	United States Department of Defense
DOE	US Department of Energy
DRE	Destruction Removal Efficiency
dscf	Dry Standard Cubic Feet
dscfm	Dry Standard Cubic Feet per Minute
ECAM	Environmental Cost Analysis Methodology
eGRID	Emissions & Generation Resource Integrated Database
EIA	US Energy Information Administration
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ETV	Environmental Technology Verification program
FP250	Ener-Core Powerstation ™, 250 kW gross output
GA EPD	Georgia Environmental Protection Department
GHG	Greenhouse Gas
HazOp	Hazard and Operability Review
HHV	Higher Heating Value
IC	Internal Combustion
kW	kilowatt
kWh	kilowatt-hour
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
LEL	Lower Explosive Limit
LFG	Landfill Gas

LFGE	Landfill Gas to Energy
LMOP	Landfill Methane Outreach Program (USEPA)
MM	million
MOA	Memorandum of Agreement
MSW	Municipal Solid Waste
MWh	Megawatt hours
NAAQS	National Ambient Air Quality Standards
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NMOC	Non-methane organic compound
NO_x	Oxides of Nitrogen
NPT	National Pipe Thread
NPV	Net Present Value
NREL	USDOE National Renewable Energy Laboratory
NSPS	New Source Performance Standard
O&M	Operations and Maintenance
O&MR	Operations, Maintenance and Repair
OMB	Office of Management and Budget
OPIS	Oil Price Information Service
PM10	particulate matter with an aerodynamic diameter up to 10 µm
PM2.5	particulate matter with an aerodynamic diameter up to 2.5 µm
ppm	Parts per Million
psi	Pounds per Square Inch
QA/QC	Quality Assurance / Quality Control
scf	Standard Cubic Feet
scfm	Standard Cubic Feet per Minute
SERDP	Strategic Environmental Research and Development Program
SO_2	Sulfur Dioxide
THC	Total Hydrocarbons
UHP	Ultra High Purity
USACE	U.S. Army Corps of Engineers
USACE	United States Army Corps of Engineers
USEPA	Environmental Protection Agency
VOC	Volatile Organic Compound
WWTP	Wastewater Treatment Plant

Executive Summary

OBJECTIVES OF THE DEMONSTRATION

The objective of this demonstration is to provide a credible, independent, third party evaluation of the performance, economics and environmental impacts of the Ener-Core Powerstation™ (FP250) technology in a landfill gas (LFG) energy recovery application at a DoD site. Ener-Core Power, Inc. was formerly known as Flex Power Generation, Inc. The evaluation was designed to provide sufficient data to allow end-users, purchasers, and others to determine the feasibility of the technology at DoD sites and other applications.

Success factors that were validated during this demonstration include energy production, emissions and emission reductions compared to alternative systems, economics, and operability, including reliability and availability.

TECHNOLOGY DESCRIPTION

The FP250 is a unique power plant that is able to generate electric power using low energy content gas or vapor while emitting low levels of atmospheric pollutants. The FP250 integrates a modified conventional micro-turbine (Ingersoll Rand MT250, now manufactured by FlexEnergy Energy Systems) of proven design with a proprietary gradual thermal oxidizer in place of the conventional turbine's combustor. Gradual oxidation is the 1- to 2-second conversion of a dilute fuel air mixture to heat energy, carbon dioxide and water. Compared to traditional combustion processes, which occur in milliseconds, the Ener-Core oxidation process is more gradual. The FP250 is able to operate using low heating value fuel sources (theoretically as low as 15 Btu/scf) that would not support operation of conventional gas turbines or reciprocating engines, which require a minimum fuel heating value of 300-500 Btu/scf.

DEMONSTRATION RESULTS

Table ES-1 summarizes the performance results for each demonstration plan objective. Key outcomes from the demonstration include:

- The FP250 met or exceeded the objectives for energy production, low NO_x emissions, NMOC destruction efficiency and GHG reductions associated with its use. NO_x emissions were much lower than the CARB 2013 standard for distributed generation.
- Exhaust CO emissions were comparable to typical emissions from gas turbines and reciprocating engines in landfill gas service, but did not meet the demonstration plan objective. CO emissions at the oxidizer outlet do meet CARB 2013 standards and a new system configuration currently offered by Ener-Core is designed to meet the CARB standard for CO.
- Based on an LCCA analysis for a typical FP250 installation, the economics for the FP250 are on par with competing distributed generation and landfill gas to energy technologies, but did not meet demonstration plan objectives at current electricity prices at Ft. Benning. The system is capable of fully automated and unattended operation, but this capability was not fully demonstrated at Ft. Benning.
- System availability and reliability did not meet the demonstration plan objectives during operations at Ft. Benning. This was due, in part, to site-specific circumstances extraneous to the FP250, including insufficient LFG supply and unusually frequent grid outages. Ener-Core worked closely with Southern throughout the demonstration to adapt the FP250 to overcome these difficulties and these efforts led to a number of enhancements to the commercial FP250 including the capability for supplemental fuel blending and full island mode operability. Ener-Core maintains that, had these

modifications been fully implemented at the start of the demonstration, system availability and reliability would have been within Ener-Core specifications (90-95%).

Table ES-1. Performance Results

Objective	Metric	Success Criteria	Result
Energy: Verify power production & quality.	Net real power delivered (kWh);	Nominal 200 kW gross continuous (1750 MWh/yr) less temperature dependent derating (to be established). Power quality meets utility inter-connection requirements	Objective met. Average net real power generation of 220 kW during oxidation-mode operation with G3 engine design.
Emissions: Verify emissions meet regulatory requirements and are lower than best alternate LFG emissions control technology.	lb/hr, lb/MWh or ppm emitted	Emissions meet or exceed CARB 2013 requirements for distributed generation and host site air permit requirements. Emissions are lower than EPA AP42 typical values for best alternate LFG control technology (boiler/steam turbine).	Objective met for NOx and NMOC. CO emissions from the turbine exhaust did not meet the objective; however, CO emissions measured at the oxidizer outlet do meet the objective.
Emissions: Verify NMOC destruction efficiency	Percent destruction efficiency for NMOC.	Destruction efficiency exceeds EPA AP42 typical value for enclosed flare (97.7%) and meets AP42 value for Boiler/Steam Turbine (98.6%).	Destruction efficiency meets the objective at 99.6%.
Emissions: Verify greenhouse gas emissions reductions.	Metric tons CO_2e/yr reduction relative to site specific baseline conditions	Greater than 800 metric tons CO2e avoided emissions due to power generation (above baseline). Greater than 6000 metric tons CO2e reduction due to destruction of CH4. Greater than 10% increase in GHG reduction compared to flare only.	Objectives met without consideration of GHG emissions due to supplemental propane use. Objectives nearly met when propane use is considered.
Assess economic performance	Simple payback (years), NPV ($)	Simple payback < 5 years; Positive NPV.	Objective not met at the current grid electricity price at Ft. Benning ($0.069/kWh). A 5 year payback is achieved at a grid electricity price of $0.18/kWh, and a positive NPV is reached at $0.10/kWh.
Determine system availability/reliability and operating impacts.	Percent availability/reliability, plus descriptive narrative.	Availability exceeds 95%. Reliability exceeds 97%. Operability is acceptable to operating authority.	Availability was 57% and reliability was 82%. Availability net of forced and planned outages was 76%.

IMPLEMENTATION ISSUES

This report provides detailed information on the performance, operability, economics, and development status of the FP250 that can be used by installation managers to assess the applicability of the FP250 for generating energy from low quality waste fuel streams at their facilities.

Installation managers should understand that the FP250, like other turbine-based technologies, requires a steady fuel supply with minimum total energy content of about 3.4 MMBtu/hr (HHV). That is, the FP250 is only capable of operating near 100 percent of rated capacity and has little or no turn-down capability. In addition, the FP250 does not tolerate excessive thermal cycling. As with larger frame size industrial gas turbines, continuous 24/7 operation is recommended and the number of restarts over the system lifetime should be minimized to avoid excessive maintenance. It is important that a sufficient, continuous fuel supply be verified during site selection. It is also important to verify the reliability of the grid interconnect (if any) at candidate sites.

At the time of this writing, the FP250 is still undergoing minor modifications to improve reliability and operability. These modifications include:

- prevention of turbine wear due to particulate breakthrough from the gradual oxidizer,
- a new startup protocol utilizing the warmer only,
- full automation of system startup,
- the capability to continue operation in ‘island mode’ to prevent unnecessary shut downs due to transient grid faults (applicable to sites where there may be frequent grid interruptions)

Ener-Core has conducted testing and/or engineering evaluations for each of these modifications at their engineering development facility and maintains that these modifications will allow the system to operate unattended with high reliability (>90%) and minimal unplanned downtime. The performance of these modifications was not verified during this demonstration.

Due to the system’s low emissions, minimal noise, and small footprint, Southern does not expect permitting or other site approvals to present any significant obstacle to implementation at most sites. For this demonstration, permitting and required approvals required minimal effort.

1.0 INTRODUCTION

Since 1996, Southern Research has conducted independent verification and demonstration studies to evaluate the performance, economics and environmental benefit of innovative clean or renewable energy technologies. As such, Southern keeps abreast of developments in such technologies and maintains a network of contacts throughout the industry. ESTCP's energy and water technology demonstration program is a natural fit with Southern's goals and expertise and Southern has been able to offer proposals that meet ESTCP's goal "to promote the transfer of innovative technologies that have successfully established proof of concept to field or production use".

The Ener-Core Powerstation™ (FP250) is able to extract useful energy from low quality waste fuel sources with low environmental impact. Southern proposed an ESTCP demonstration of the FP250 based on an assessment that the technology has the potential to help address energy security and environmental sustainability mandates and goals established by the U.S. Department of Defense (DoD). In addition, Southern's assessment was that the FP250 technology was sufficiently well developed and market ready that rapid deployment would be feasible following a successful demonstration.

A valuable resource for the production of renewable energy is landfill gas from DoD owned landfills at domestic bases. The FP250 is ideally suited for this application and Ener-Core successfully demonstrated a prototype of the technology using landfill gas prior to the ESTCP demonstration (see section 2.2).

Early in this project, Southern identified and collected data from 471 landfills operated within DoD. This information was used to direct site selection for the FP250 demonstration as well as to assess the potential benefit of this application within DoD. A database and report resulting from this effort were submitted to ESTCP in 2010 [3]. Site selection activities for the demonstration were also completed in 2010 and arrangements were made with Ft. Benning to host the demonstration at their 1st Division Road landfill.

In late 2010, Ener-Core provided drawings and specifications for the Ft. Benning installation and, during the first weeks of 2011, participated in a formal hazard and operability review (HAZOP) conducted by Southern to identify and provide for mitigation of all hazards and operability concerns. In March 2011, Southern observed a successful factory acceptance test (FAT) of the FP250 at a test facility outside San Diego, CA. Site preparation and construction/installation began at Ft. Benning during April 2011 and the system was first operated on July 12, 2011. Southern completed installation of monitoring and data acquisition equipment and began collecting monitoring data on July 5, 2011.

Commissioning and shakedown activities continued into the Fall of 2011 and the system was officially deemed operational on September 29, 2011. A ribbon cutting ceremony was held at Ft. Benning on November 8, 2011. During late 2011 and early 2012, Ener-Core continued to refine the system while accumulating operating hours. The one year demonstration period was officially concluded on September 29, 2012; however operations continued through November 18, 2012 to allow for completing emissions testing. Details on system operations, modifications and performance are provided in this report.

1.1 BACKGROUND

The DoD occupies over 620,000 buildings at more than 400 installations in the U.S, spending over $2.5 billion on energy consumption annually. Reductions in energy consumption from these facilities and utilization of renewable energy sources has become a primary goal of the DoD for several reasons: (1) to reduce emissions and environmental impacts related to power production and consumption in response to air pollution and climate change issues; (2) to reduce costs associated with energy consumption, resulting in additional resources aimed at DoD primary missions; and (3) to improve energy security, flexibility, and independence. More recently, these priorities have been re-enforced through the release of Executive Order 13423, Strengthening Federal Energy, Environmental and Transportation Management (January 2007).

The FP250 utilizes a conventional 250 kW micro-turbine of proven design with many years of field operation. The major modification made by Ener-Core replaces the conventional combustion chamber with a thermal oxidizer, enabling the system to operate with low heating value fuels and with low atmospheric pollutant emissions – as thermal oxidizers are conventionally used as air pollution control devices. The FP250 is able to operate using low heating value fuel sources that would not support the operation of conventional devices such as conventional gas turbines or IC engines. The FP250 requires less waste gas cleaning than conventional engines and gas turbines, and requires a lower fuel supply pressure compared to gas turbines. Conventional turbines and IC engines need fuel cleanup that typically involves water removal, chilling and media treatment. Typical turbines require fuel delivery pressures of 100 psig or higher, while reciprocating engines require fuel delivery at 2 psig or higher. The FP250 uses gas delivered at 5 psig.

The FP250 is potentially applicable to a variety of DoD sites, including landfills, facilities with anaerobic digesters for wastewater treatment, painting or printing operations, VOC remediation systems, as well as typical fossil fuel applications. An important additional benefit of the FP250 includes offsetting the cost and environmental impact of destruction of these waste streams, which is often energy intensive and may result in significant atmospheric emissions

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this demonstration is to provide a credible, independent, third party evaluation of the performance, economics and environmental impacts of the FP250 technology in a LFG energy recovery application at a DoD site. The evaluation was designed to provide sufficient data to allow end-users, purchasers, and others to determine the feasibility of the technology at DoD sites. Such information is needed to build market acceptance of the technology within DoD and other potential markets.

Success factors that were validated during this demonstration include energy production, emissions and emission reductions compared to existing systems, economics, and operability, including reliability and availability.

1.3 REGULATORY DRIVERS

Energy security, environmental sustainability, and long-term savings are all drivers for the subject technology. On October 5, 2009 President Obama issued Executive Order 13514 [3] titled "Federal Leadership in Environmental, Energy and Economic Performance". Among other things, this Order challenges Federal agencies to increase energy efficiency, reduce direct and indirect greenhouse gas emissions and prevent pollution. Executive Order 13423, signed January 24, 2007, also directs Federal agencies to increase use of renewable energy. The Energy Independence and Security Act of 2007 also emphasized the development and use of renewable energy. The Energy Policy Act (EPAct) of 2005 seeks to promote innovative technologies that avoid greenhouse gases, including renewable energy technologies.

The implementation of the FP250 using landfill gas has potential impacts in all of these areas by:

- Using a renewable fuel resource (landfill gas);
- Improving energy efficiency by reducing energy consumption associated with flare use and utility transmission/distribution losses;

- Reducing greenhouse gas emissions by offset of grid electricity and destruction of methane (if not flared)

In NAAQS non-attainment areas, or other areas with strict emissions limits such as California, the FP250 offers the means for DoD installations to meet applicable air quality regulations while generating power from renewable or non-renewable energy sources.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The FP250 is a unique power plant that is able to generate electricity using low energy content gas or vapor while emitting low levels of atmospheric pollutants. The FP250 integrates a modified conventional micro-turbine (Ingersoll Rand MT250, now manufactured by Flex Energy Systems) of proven design with a proprietary gradual thermal oxidizer in place of the conventional turbine's combustor. Gradual oxidation is the 1- to 2-second conversion of a dilute fuel air mixture to heat energy, carbon dioxide and water. Compared to traditional combustion processes, which occur in milliseconds, the Ener-Core oxidation process is more gradual. The FP250 is able to operate using low heating value fuel sources (theoretically as low as 15 Btu/scf) that would not support the operation of conventional gas turbines or reciprocating engines, which require a minimum fuel heating value of 300-500 Btu/scf.

The FP250 is theoretically cable of utilizing fuels with heating values as low as 15 Btu/scf, though practical considerations for fuel supply equipment and fuel rate control will increase this minimum value somewhat in most applications. Conventional gas turbines and reciprocating engines require fuels with minimum heating values in the range of 300-500 Btu/scf. In the Ft. Benning demonstration, the FP250 was able to operate on landfill gas alone with fuel heating values in the range of 250 Btu/scf.

During normal operation, the fuel gas (or vapor), regardless of energy content, is diluted with ambient air to 15 Btu/scf and drawn into the turbine's compressor. Following condensate knockout, the LFG is filtered with a coarse filter and also flows through the air inlet filter of the turbine's compressor. Some fuel sources may require additional treatment to remove liquids/water and particulates if they are excessive. The compressed air/fuel mixture (~55 psia) enters the thermal oxidizer where contaminants are destroyed and energy is extracted to power the turbine and generate electricity. Exhaust gas from the turbine is used to preheat the air/fuel mixture entering the oxidizer. Between the oxidizer and the turbine, a hot gas filter is used to remove fine particulates that may be present due to siloxane oxidation, oxidizer media or insulation breakdown, or corrosion of hot metal components exposed to the hot gas stream.

During startup, the oxidizer must be preheated and the turbine brought to operating conditions before the system can operate in steady state gradual oxidation mode. For this purpose, a startup system is provided that fires combustors at the oxidizer and turbine inlets. Table 1 summarizes the operating states for the FP250 and auxiliary systems (startup and blower skids). Figure 1 provides an overall schematic flow diagram for the system. Figure 2 shows the FP250 installed at the 1st Division Road landfill.

The FP250 is potentially capable of utilizing waste streams other than landfill gas as the fuel input, such as paint booth or other VOC-laden industrial process exhausts, off-spec fuels, waste solvents, and other low BTU or high contaminant waste gases, liquids or vapors. The FP250 is also available with a heat recovery option for applications where there is a local use for the recovered heat.

Table 1. FP250 Operating States

Parameter	Operating State			
	Start	Warm up	Transition	Oxidation Mode
Turbine Speed	low and ramping	ramping to full	full	full
Generator Output	none	zero to ramping	ramping to full	full
Start Skid	on	on	ramping to off	off
Blower Skid	off	off	ramping to on	on

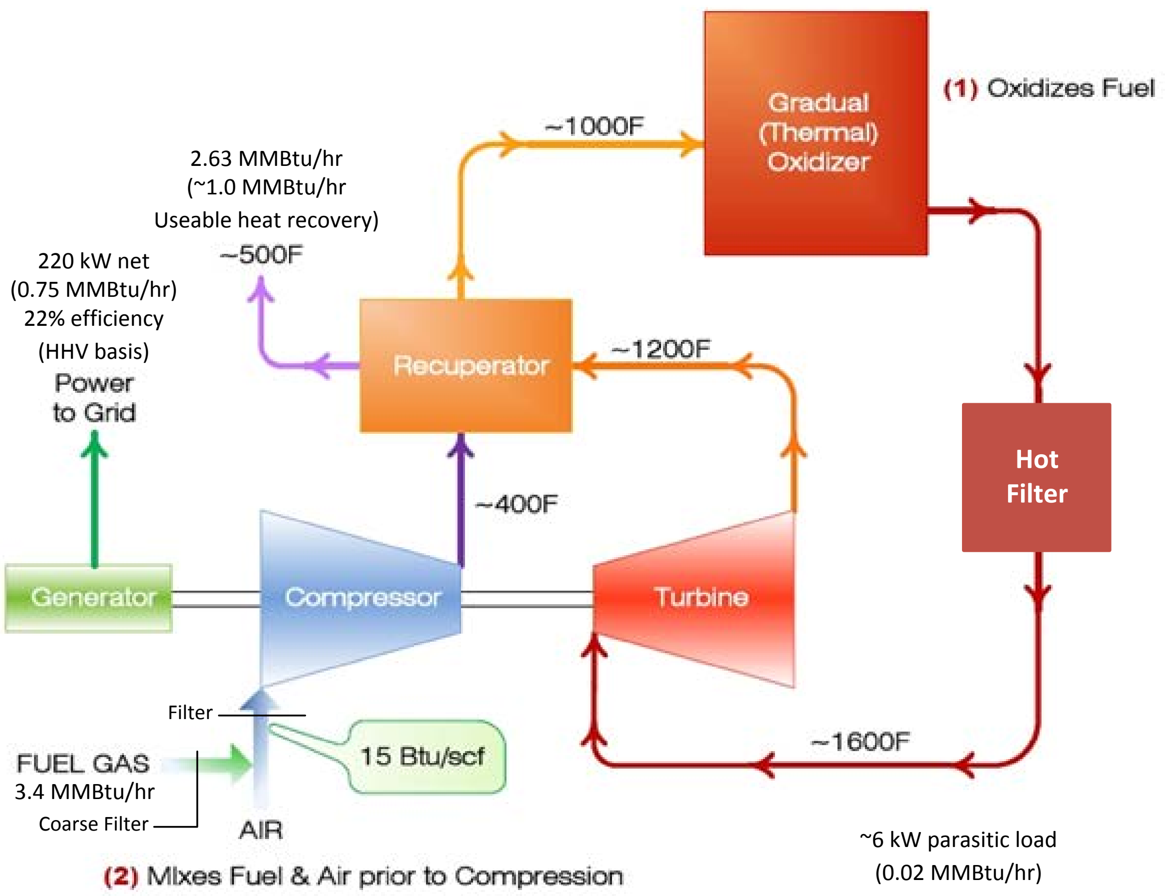

Figure 1. FP250 Schematic

Figure 2. FP250 installed at 1st Division Road Landfill

2.2 TECHNOLOGY DEVELOPMENT HISTORY

For over a decade prior to this demonstration, Ener-Core (and its predecessor companies) pursued the development of a power plant that could operate on a wide variety of low quality fuels. Research was supported by government grants from the Department of Energy, the National Renewable Energy Laboratory, California Energy Commission, and other agencies. In 2002 Ener-Core received a U.S. patent for a “Method for Collection and Use of Low Level Methane Emissions” (US 6,393,821 B1).

The original design employed a catalytic combustor coupled with a 30 kW micro-turbine. The useful life of the catalytic combustor was severely compromised by contaminants in the waste gas streams of interest. Experience with the catalytic unit led to the adoption of a non-catalytic thermal oxidizer in its place. A thermal oxidizer was chosen due to its ability to tolerate contaminants in waste streams.

A prototype oxidizer-based system was assembled in October 2008, with the first successful operation accomplished after 10 months of development testing. Re-packaging of the prototype system into a 100kW pilot field system (FP100) was started in November, 2009. The pilot system was delivered to Lamb Canyon Landfill in Beaumont, California, in May 2010, and was successfully operated on landfill gas starting in June 2010. By September 2010, the pilot unit had accumulated over 480 hours of operation on landfill gas. The pilot plant demonstrated the ability of the oxidizer-based system to continue operation during intermittent fuel supply interruptions. The pilot plant operation continued at Lamb Canyon for engineering control development and integration with the day to day operation at a landfill until early 2011, accumulating 648 total hours of operation before it was decommissioned. The FP100 was a proof of concept prior to scaling to the FP250 and was never intended for commercial deployment. The unit was in operable condition at the time of decommissioning, though turbine wear had been observed.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The chief advantage of the FP250 is the ability to utilize low quality fuel sources to provide electrical energy and heat recovery. Since these low value fuel sources are often waste streams, a related advantage is reducing costs associated with treatment of these wastes and realizing offsets of energy and emissions associated with waste treatment. The FP250 configuration evaluated at Ft. Benning also eliminates the need for a separate fuel compressor, as the blended low-BTU fuel-air mixture is compressed by the turbine's integrated compressor.

The FP250 incorporates a proprietary thermal oxidizer within a recuperated Brayton cycle. Thermal oxidation is an effective means of destroying non-methane organic compounds (NMOC) and other organic pollutants. As a result, observed FP250 emissions of atmospheric pollutants are lower than alternate LFG destruction/utilization technologies such as conventional gas turbines or reciprocating engines. In addition, the oxidizer minimizes NO_x formation while destroying CO and VOCs.

The FP250 operates without a complex gas cleanup system. The system is designed to trap particulates formed from siloxane oxidation within the oxidizer while destroying other pollutants. The FP250 runs quietly (<83 dBA at 1 m), making it potentially suitable for locations near residential or office areas.

The FP250 can be used with fuel sources as small as 3.4 million BTU/hr (56 scfm of 100% methane) and multiple units can utilize larger sources. Where a fuel source smaller than 3.4 million Btu/hr is available, supplemental natural gas or propane can be blended with the available waste fuel to allow the system to operate. Since the unit is designed to be fuel flexible and adaptable to changes in fuel concentration, it can be utilized with fuel sources that change energy density levels (Btu/scf) during operation from a minimum of zero (for brief periods) to a maximum determined by the fuel delivery and control equipment which is designed specific to each application. During the acceptance test, Southern observed continued FP250 operation during a complete, 3-minute, shut off of the fuel source. An average fuel heat content of 3.4 MMBtu/hr is required for operation.

The chief limitations of the FP250 are that it is unproven in applications beyond energy recovery from landfill gas and, as a newly commercialized technology, has not yet achieved a long-term record of continuous field operation. In the FP250 configuration demonstrated at Ft. Benning, the LFG is diluted with ambient air and aspirated directly into the turbine's compressor with minimal pretreatment (see section 2.1). Some alternative fuel sources (e.g., spent solvent vapors) may require additional gas cleaning, cooling, or pretreatment to avoid excessive compressor maintenance.

Life cycle costs and the levelized cost of energy for a typical FP250 installation are on par with competing turbine-based distributed generation and LFGE technologies. A detailed analysis of comparative costs is presented in section 5.3.7.

3.0 FACILITY/SITE DESCRIPTION

The demonstration took place at the 1st Division Road landfill at Fort Benning, Georgia. The following sections provide a detailed characterization of the Ft. Benning site conditions with respect to FP250 operation and the conduct of the demonstration. Necessary requirements and site layout for FP250 installations at other sites are also addressed.

3.1 FACILITY/SITE LOCATION, OPERATIONS AND CONDITIONS

The 1st Division Road Landfill is located on Ft. Benning grounds near the intersection of 1st Division Road and US highway 27/280 (Figure 5). The landfill was initially reported by Ft. Benning to contain approximately 48 acres of waste material at an average depth of 30 feet (approximately 2.3 million cubic yards waste volume). During the demonstration, however, it was discovered that the actual fill area is approximately 26.5 acres and the best estimate of waste-in-place volume is approximately 1.5 million cu yd. The density of this material is unknown, but the best estimate is about 1000 lbs/yd^3 yielding a waste in place mass of about 750,000 tons [1].

The landfill accepted municipal solid waste and construction/demolition debris starting in 1985 and continuing into1997. The landfill was formally closed in 1998. The landfill is unlined and has a sand drainage layer that should allow leachate to filter through and leave the site. The cap consists of a subgrade layer, a geocomposite liner, and 24 inch cover soil layer.

The electric power supplier on base is Flint Energy. Power is supplied to Flint Energy by Georgia Power at three entry points on the base. All sub-metering within the base by Flint Energy is for the purpose of allocating operational costs within Ft. Benning. The power generated by the FP250 offsets on-base electricity consumption. There was no commercial export agreement required with Flint Energy. The point of interconnection with the Flint Energy grid is within approximately 100 yards of the FP250 location.

3.1.1 LFG Supply

Initial estimates of expected LFG collection volume during the demonstration were based on monthly wellhead monitoring data collected from June 2008 through January 2011. These data showed aggregate landfill gas production rates averaging 190 scfm (range 2 to 635 scfm) at an average methane content of 42 percent (range 26 to 58 percent) – or an average of 4.8 MMBTU/hr. The monthly monitoring was conducted only at the wellheads and there was no historical monitoring of the total LFG as delivered to the flare. Further confirmation of the expectation that there would be sufficient fuel supply to operate the FP250 came from a 2004 report that estimated the landfill was capable of producing 700 scfm of landfill gas at 40 to 50 percent methane from 2005 through 2020-2025 [2].

During FP250 commissioning over the Summer of 2011, it became apparent that the landfill was not consistently producing LFG of sufficient quantity and quality (heat content) to allow the FP250 to operate. In response, Ener-Core installed a system to augment LFG with propane to provide sufficient fuel heat input to allow the system to operate. At the same time, Southern initiated efforts to investigate whether LFG production from the landfill could be increased.

It should be noted that the LFG collection system was designed to prevent off site methane migration and was never intended to supply LFG for energy production (see section 3.1.2 below). As such, well spacing, well construction, the design and construction of the collection system piping and blowers, and operating procedures for the LFG collection system were not optimized for an LFG to energy application.

Throughout the demonstration, prevention of offsite methane migration necessarily remained a priority over LFG production and quality, although the two goals are not mutually exclusive.

At the start of the project, Southern requested that LFG flow and gas concentrations (for methane, oxygen and carbon dioxide) in LFG delivered from the extraction system to the flare skid be regularly monitored and reported and began receiving and compiling these data in September 2011; however LFG flow measurements at the flare did not become available until November 2011. Figure 3 shows the heat content of extracted LFG from November 2011 through November 2012. On average over this period, the landfill produced about 3.0 MMBtu/hr, or about 88 percent of the energy required to operate the FP250. Typically, the landfill would produce higher quality fuel gas for a few days following warm/wet weather or after a several day period when the extraction system was shut down.

Referring to Figure 3, the reduced degree of scatter in the LFG heat recovery data after May 2012 is partly due to a change in operating regime where extraction system blowers were shut down and the FP250 fuel delivery system provided the suction on the extraction system instead of the blowers. In addition, after May 2012, Ener-Core's on site operator began to adjust individual wellheads as needed to optimize LFG extraction (so long as mitigation of methane migration was not compromised).

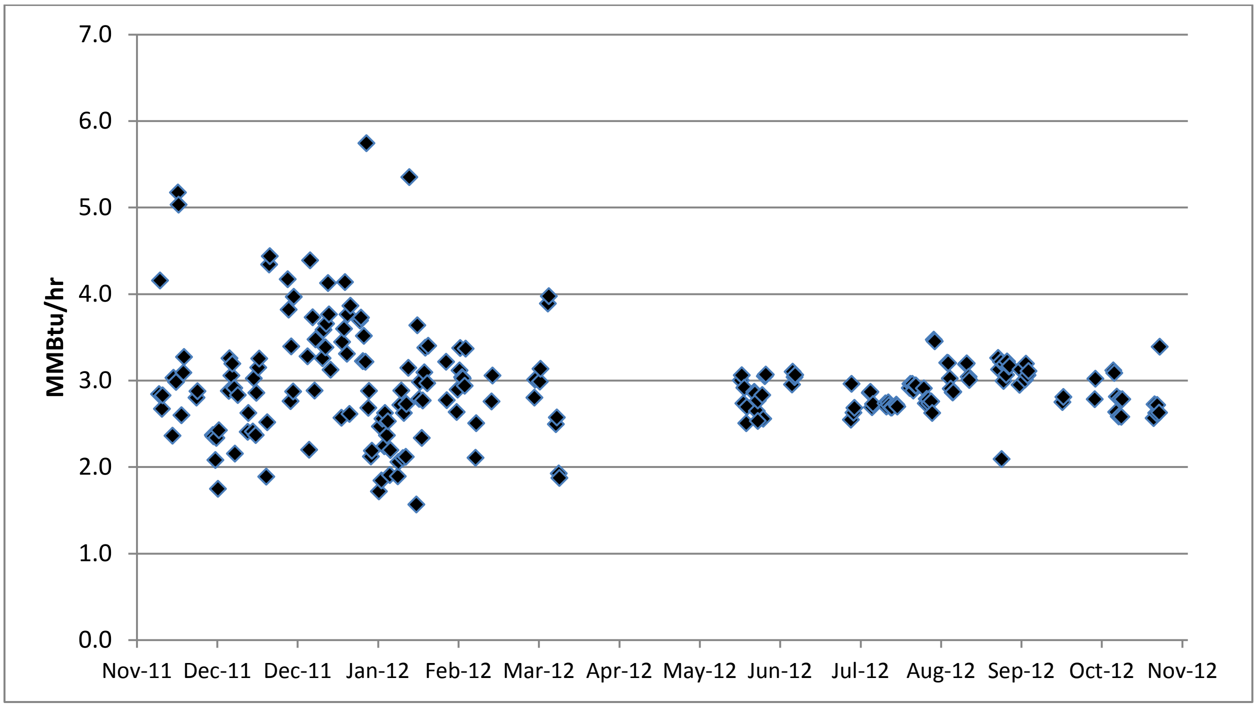

Figure 3. LFG Energy Content

Southern contracted with SCS Engineers to assess the condition of the landfill and extraction system. SCS conducted a field survey on October 2011 and made a number of management and structural recommendations to improve the LFG extraction performance of the landfill while continuing to mitigate offsite methane migration. Management recommendations included balancing extraction system vacuum with well head production to prevent extraction in excess of the LFG production rate, and improving the effectiveness and increasing the frequency of routine wellhead rebalancing. Structural recommendations included improving maintenance and repair of extraction system piping and retrofitting sleeves in the wellhead casings to cover piping perforations to a depth of 15 feet in order to prevent atmospheric air intrusion into the extraction system [1]. With the support of Ft. Benning, these recommendations were carried out to the extent practicable, but it was not feasible to install retrofit wellhead casing sleeves.

In addition, SCS developed a site-specific model of expected LFG production and recovery rates. Modeled LFG recovery rates for the best fit case (mid-level assumptions) closely matched measured LFG extraction rates (see Figure 4)[1]. Based on this comparison, it was concluded that the landfill was producing about the expected amount and quality of LFG and that the initial production estimates based on wellhead monitoring were erroneous (probably due to aggregated errors in LFG flow readings taken at each wellhead as opposed to measurement of total flow at the flare).

Based on the modeled LFG recovery rate over time, it is expected that LFG recovery will fall from its current rate of 3.0 MMBtu/hr to 2.0 MMBtu/hr by 2017 (59% of the energy required to operate the FP250) and to 1.0 MMBtu/hr by 2026 (29% of the energy required to operate the FP250). In 10 years (by 2023), LFG recovery is expected to fall to 1.3 MMBtu/hr, or 38% of the energy required to operate the FP250. Considering the cost of supplemental fuel, the economic analysis presented in section 5.3.5 provides an estimate of the number of years that it is expected that the FP250 at Ft. Benning can be operated on a cash flow neutral basis.

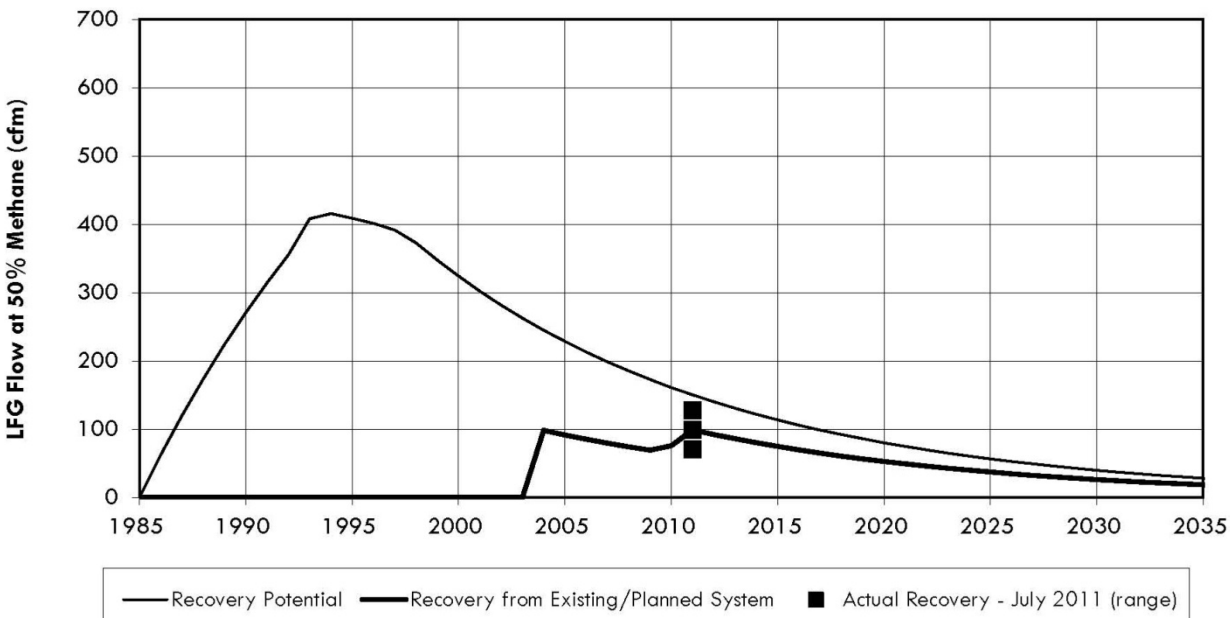

Figure 4. Modeled LFG Recovery Projection – Mid-Range Estimates

3.1.2 LFG Extraction System History

In 1993, three methane and ten groundwater monitoring wells were installed along the western property boundary. Methane levels exceeding the lower explosive limit were detected in the wells. In 1996, seven additional methane and eight additional groundwater monitoring wells were installed. In 1998, 39 passive landfill gas vent wells were installed in compliance with the Georgia Department of Natural Resources approved closure plan. In 1999, three additional methane monitoring wells were installed off-site to the west of the landfill due to elevated methane detected at the landfill boundary.

In 2003, landfill gas generation rates were quantified based on vent performance tests. Based on this, the landfill was estimated to be capable of producing 700 scfm of landfill gas at 40 to 50 percent methane from 2005 through 2020-2025. Up to 40 percent of the total landfill gas generated was estimated to be escaping through westward migrating gas. [2]

In 2004, 18 of the 39 passive vent wells were converted to an active extraction system and an open ‘candlestick’ flare system was installed to safely destroy the collected gas. This measure was intended to mitigate problems with westward migration of the gas offsite.

In 2008, the gas extraction system was overhauled due to subsidence of the landfill material having caused the underground piping of the gas collection system to become ineffective. Improvements were made to enhance landfill cover and drainage and the gas collection headers were installed on adjustable supports above ground.

Due to continued problems with offsite methane migration, the gas collection system was expanded to 31 wells in October 2010 and an additional blower was installed to increase gas extraction. Figure 5shows the location of the landfill. Figure 6 shows the complete gas collection system as modified in September 2010.

Figure 5: 1st Division Road Landfill Location

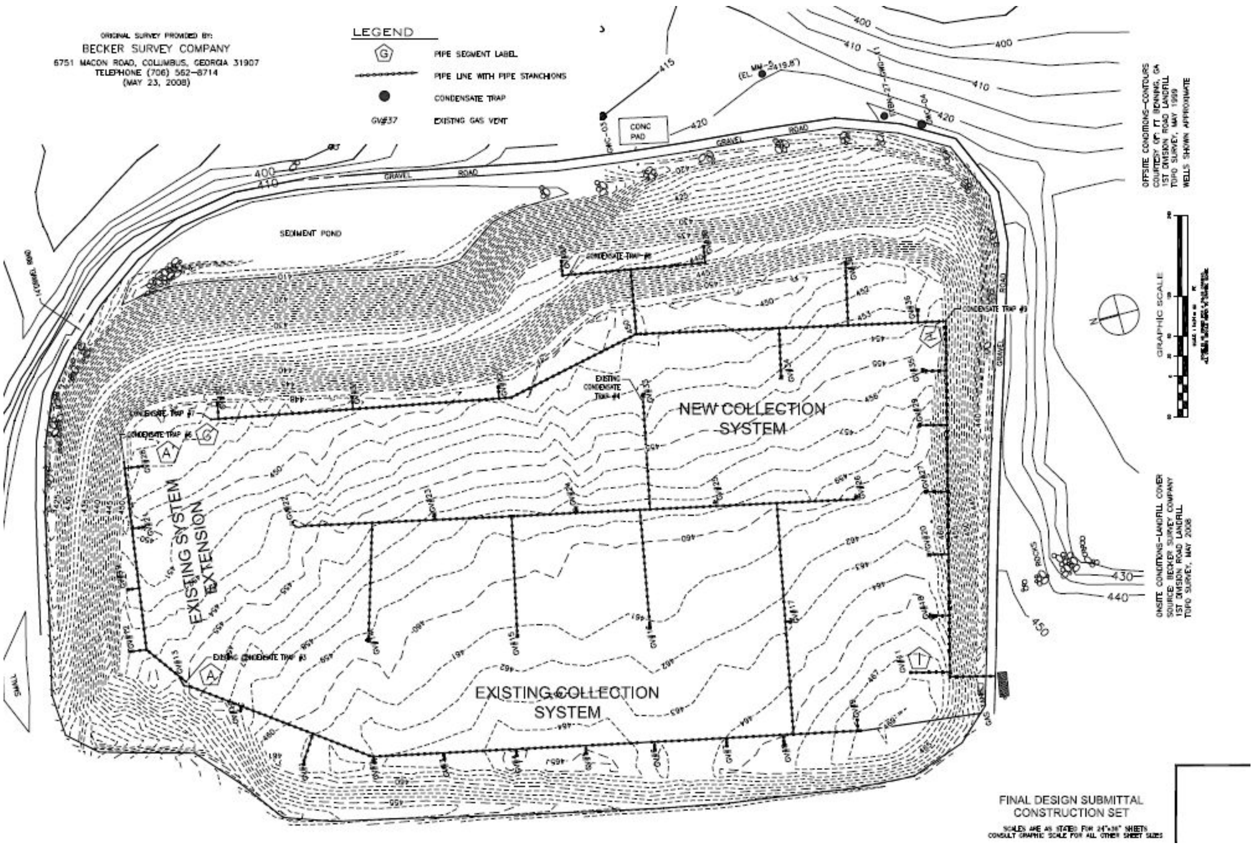

Figure 6: 1st Division Road Landfill LFG Collection System

3.2 SITE/FACILITY IMPLEMENTATION CRITERIA

3.2.1 Siting Criteria

The most essential criterion to support FP250 operation at a given site is the availability of a fuel source comprising at least 3.4 MMBtu/hr in fuel heating value. As the FP250 is fuel flexible, potential fuel sources include landfill gas, digester gas, VOC exhaust from paint booths, or contaminated or spent solvents or liquid fuels. Table 2 gives minimum fuel requirements for operation of a single FP250 unit on various fuels.

Table 2. Minimum fuel requirements for FP250 operation on various fuels

Source	Fuel Flow Rate	Fuel Energy	Notes
Paint Booth VOC	3,778 scfm	15 Btu/scf	Energy contents lower than 15 Btu/scf will require supplementary fuel.
Landfill Methane	112 scfm	506 Btu/scf	The energy content of the gas stream is based on a 50% methane concentration. If the concentration is lower, the flow rate will need to be higher.
WWTP Digester Gas	112 scfm	506 Btu/scf	The energy content of the gas stream is based on a 50% methane concentration. If the concentration is lower, the flow rate will need to be higher.
Liquid Fuels (JP8)	223,604 gal/year	18,500 Btu/lb	Waste liquid fuels are normally inventoried by DoD installations contacted on an annual basis. Usage based on continuous FP250 operation (8760 hrs/year).
Liquid Fuels (Solvent)	330,933 gal/year	12,500 Btu/lb	
Note: The density for liquid fuels is taken as 7.2 lb/gallon. Fuel flow based on 3.4 MMBtu/hr required energy input.			

The FP250 is designed for year round outdoor operation at temperatures ranging from -10° to 115 °F. Operation at lower ambient temperatures is possible with special modifications.

The FP250 and balance of plant equipment at Ft. Benning occupies a fenced enclosure covering approximately 3600 square feet (60 X 60 feet) including space for startup and supplementary propane fuel storage. A footprint approximately half this size would be possible if there were no need for supplementary fuel storage. The site soil conditions must be suitable for supporting the weight of the equipment and concrete pads. The heaviest integrated components (turbine, oxidizer, piping and supporting steel work) weigh about 25 tons combined and occupy an area of about 12 X 24 feet.

The FP250 operates quietly at 83 dBA at 1 meter, making the unit suitable for installation near residential or office areas. A low sound option is available that reduces the sound level to 77 dBA at 1 meter.

The FP250 can be connected for grid-parallel, dual-mode, or grid-isolated electrical generation. In the event of a grid outage, the FP250 is capable of automatically switching to island mode operation utilizing the generator braking resistor bank to take the load until the grid comes back online.

If there is a local use for recovered heat, the FP250 can be fitted with an integral heat recovery unit capable of recovering about 1 MMBtu/hr as hot water from the exhaust gas stream. This would more than double the overall thermal/electrical efficiency of the unit. Details on temperatures and flows for the heat recovery unit are given in section 5.2.1.

3.2.2 Demonstration Site Representativeness and Replication Potential across DoD

As an initial phase of this project, Southern compiled data from 471 landfills at DoD sites across all service branches. Based on this study, 104 sites were considered to potentially be suitable for installation of at least one FP250 in terms of best estimates of LFG recovery at each site [3].

Six DoD landfill sites with the greatest potential were investigated in further detail as part of the site selection process for this demonstration. Candidate sites were selected based on:

- Sufficient LFG recovery for FP250 operation
- Years since closure
- Existing infrastructure such as an LFG collections system and proximity to electrical interconnection
- External factors such as whether a premium is placed on renewable energy at the site, whether there is a local use for recovered heat, and other interests particular to the installation

At three of these sites, Southern was unable to obtain sufficient technical data to evaluate site suitability due to lack of sustained interest on the part of base personnel. At two more sites, there was initial interest, but competing priorities or interests prevented the base from committing support to the demonstration project. Southern selected Ft. Benning as the demonstration site due largely to the presence of strong support at the base and effective advocacy of the project by base personnel. The presence of a strong and effective advocate who is able to enroll support from other on-site stakeholders is a key success factor for a demonstration project [4].

Phase II of this project proposed to demonstrate the FP250 at a second site, ideally taking advantage of non-LFG waste streams within DoD facilities and operations that would represent further opportunities to produce useful energy from low- or negative-value fuels. In an extended effort to identify a second demonstration site, Southern made over 100 contacts at DoD bases and installations where suitable waste streams (landfill gas, digester gas, VOC exhaust from paint booths, or contaminated or spent solvents and liquid fuels) might be present. Southern received significant support in this effort from ESTCP and Ener-Core; however, the effort to find a second site was unsuccessful [5].

The reasons for the inability to identify a second demonstration site had to do with a combination of technical, fiscal, and organizational factors depending on the site and the fuel source. One important factor was that Phase II funding did not provide for the purchase and installation or modification of a second FP250, so the capital costs of the project would have to be recovered through a power purchase agreement (PPA) or similar contractual arrangement. The need for a PPA or similar agreement added complexity and limited the number of potential sites.

Through telephone and email contacts with base personnel, Southern learned that paint booth solvent and soil remediation vapor fuel source applications for the FP250 are marginal due to low available energy content and intermittent availability. While the FP250 is suited to low energy content fuel sources, the heat content for paint booth and soil remediation vapors appears to be near the threshold for FP250 operability (15 Btu/scf). Fuel delivery and control systems to manage the very large volumetric flows required were considered too costly or complex, especially given the intermittent availability of these fuel sources.

Direct destruction of contaminated oils or fuels has potential, but there are high technical risks and challenges associated with these waste fuel sources. Such a system would require injection of the waste stream into the thermal oxidizer. These waste streams are typically highly heterogeneous and the injection system must either pre-treat the waste stream so that it behaves reasonably consistently when injected, or separate the stream by range of viscosity and/or density. A substantial level of bench testing and design of system modifications and operating/application development work would be required before a demonstration could commence.

The spent solvent application appeared promising, but the requirement for a hazardous waste disposal permit was a barrier for the installations contacted. The energy content of the spent solvents is high, and they are readily volatilized. Technically, use of spent solvent requires some modification/fuel processing to present a dilute vapor stream at the inlet to the FP250 turbine compressor stage. However, the requirement for internal modifications to the system is avoided and the use of spent solvent is technically less challenging than the waste oils destruction application.

Use of methane from waste water treatment facilities could easily be achieved if a suitable site could be identified. Little modification to the FP250 would be required for this application. An influent rate of two million gallons per day at a wastewater treatment plant with an anaerobic digester would produce enough methane to support the FP250. Southern investigated waste water treatment facilities at 35 sites. Southern found that in most cases, waste water treatment plant operations were contracted to private sector corporations, which presents organizational/contractual challenges for a demonstration project. In addition, Southern found that, in many cases, low or intermittent influent rates, influents unsuitable for digestion, lack of anaerobic digesters, or insufficient digester gas capture capabilities made the site unsuitable for the FP250.

Southern made contacts at several dozen bases with landfills. In the majority of cases, the landfills did not have existing gas collection systems and the cost and lengthy time horizon for installation of a collection system made the sites unsuitable for a demonstration project. In other cases, the landfills were dedicated to construction and demolition debris or other material with very low or no methane generation potential. When a collection system and sufficient LFG *were* available, the collected gas was already being utilized or sold offsite. In other cases, there was simply insufficient interest in the project from energy managers or other potential stakeholders at the base.

3.3 SITE-RELATED PERMITS AND REGULATIONS

Several permit modifications and internal approvals were required in order to commence construction and installation of the FP250 at the Ft. Benning site. Permits and approvals include the following:

- Site plan drawings were submitted to the Georgia EPD Solid Waste Department to obtain a minor modification to the landfill permit to allow locating the FP250 equipment approximately 25 feet south and east of the existing flare enclosure within a fenced area of approximately 60 X 60 feet.
- A Record of Environmental Consideration (Form 144) was prepared by Dorinda Morpeth and submitted for internal review to obtain necessary approvals from Ft. Benning environmental and public works departments to begin construction.
- Southern Research confirmed that there were no ESTCP engineering review/approval requirements before construction could commence.
- The GA EPD Air Permit Engineer indicated that the air permit modification can be handled as an off-permit request, as the planned turbine installation is considered an insignificant source and NSPS does not apply. Information on potential to emit and other aspects of the project was submitted to the GA EPD for review.
- A Memorandum of Agreement (MOA) was prepared and submitted for approval by Ft. Benning’s Energy Manager and Garrison Commander. The MOA provides a basic description of the project, funding, duration, and outlines the responsibilities of each party involved.
- A hazard assessment and site health and safety plan were prepared and presented to the Ft. Benning Energy Manager for approval.
- An electrical interconnection agreement was established between Ft. Benning and Flint Energy.

Southern determined that there were no additional permitting or regulatory requirements necessary to construct and operate the FP250 system at Ft. Benning.

Due to the FP250’s low emissions, minimal noise, and small footprint, Southern does not expect permitting or other site approvals to present any significant obstacle to implementation at most sites.

The Ft. Benning demonstration unit did not meet CARB 2013 standards for CO at the turbine exhaust; however, for California installations, Ener-Core's new 'ultra low emissions' configuration could be installed. This configuration requires a fuel compressor to inject the fuel directly into the oxidizer rather than aspirating the fuel into the turbine's compressor, avoiding related excess CO emissions (see section 5.2.2). In addition, CARB 2013 defines the Best Available Control Technology level in California for waste gases (digester, landfill and associated oil field gases). The rule is used as exemption guidance for the different air districts. Each air district has its own set of rules and permits can be obtained for a de minimis source such as the FP250.

4.0 TEST DESIGN AND ISSUE RESOLUTION

The FP250 demonstration plan was designed to provide all data required to satisfy objectives as defined in the demonstration plan and to provide additional information as needed to ensure the quality and representativeness of these data.

As this was a distributed generation project with combined heat/power applicability and is supported by EPA's Environmental Technology Verification (ETV) program, the ETV Generic Verification Protocol for Distributed Generation and Combined Heat and Power Field Testing [6] applies. As applicable, testing and data analysis methods and QA/QC requirements in this demonstration plan conform to the Generic Protocol.

4.1 CONCEPTUAL TEST DESIGN

At a minimum, all that is required to demonstrate achievement of the FP250 performance objectives is monitoring the net power production, conducting an emissions test, and compiling and analyzing economic and operational data. In addition to these basic requirements, the following additional supporting determinations were made:

- The heat input to the system was measured during operations so that the system efficiency could be determined.
- Ambient conditions were monitored in order to determine variation in power output and system efficiency with varying temperature, humidity and barometric pressure.
- Selected FP250 operating parameters (e.g., oxidizer inlet/outlet temperatures, LFG feed rate, run state) were monitored as an indication of overall system 'health' and operational status. Exhaust temperature was monitored in order to support an estimate of the heat recovery potential of the system. The system installed at Ft. Benning is not currently equipped for heat recovery.
- Landfill gas extraction system health and gas production were monitored via monthly wellhead checks and flow and methane concentration of the LFG delivered to the flare.

4.2 BASELINE CHARACTERIZATION

The baseline datum for this test is simply continued operation of the extraction system and flare without the FP250. As such, the overall LFG extraction rate and gas quality are inconsequential to the objectives of the demonstration so long as sufficient methane is produced to operate the FP250. Excess LFG would be consumed by the flare. In practice, as discussed above, the LFG recovered by the extraction system was normally insufficient to operate the FP250. The flare was bypassed during FP250 operation and supplemental fuel (propane) was used to make up the balance of the fuel energy required.

The majority of GHG reductions attributable to the FP250 result from utility offsets due to the power produced. The difference in methane destruction efficiency between the FP250 and the flare is small and is it is not practical to measure the actual destruction efficiency of the flare. Thus, the existing 'baseline' system played no significant role in determining performance results for this demonstration apart from the estimated cost of installing a gas extraction system and flare if it does not already exist at a given site.

4.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Figure 7 is a site plan of the layout of the FP250 system components in relation to the existing flare pad located immediately south of the landfill area. The function of the FP250 and integral components has been described in section 2.1 above.

The propane skid consists of two 1000 gallon propane tanks, an evaporator and controls to provide propane fuel for startup and fuel augmentation as needed.

The fuel delivery skid consists of condensate removal followed by a positive displacement compressor to provide up to 310 scfm saturated LFG at a delivery pressure of approximately 5 psi. The LFG is pressurized to allow for downstream flow control that regulates the fuel supply into the ambient air aspirated into the turbine's compressor.

The load bank (generator braking resistor) is sized to take the entire output of the FP250 and normally receives the load for brief periods during startup and shutdown when the FP250 is not synchronized to the grid. The load bank can also be employed to allow the system to continue operating in standby 'island' mode when the grid is offline. Grid faults were unusually frequent occurrences at the demonstration site, occurring up to several times per month.

Ener-Core implemented a standby 'island' mode solution allowing the FP250 to operate for up to 5 minutes during a grid interruption; however full 'island' mode capability, including the ability to power the fuel delivery skid from the FP250 during a grid outage, was not fully implemented as of the end of the demonstration period. Ener-Core has provided specifications for switchgear and controls necessary to implement full island mode capability and has recommended that Ft. Benning implement these modifications prior to taking over operation of the system in order maximize performance and avoid excessive thermal cycling.

The LFG fuel is taken off the existing extraction system piping at a tee located between the extraction system blowers and the flare. The initial plan was to operate the extraction system in the usual manner. The FP250's fuel delivery system compressor would pull off the fuel required to operate the FP250 and any excess LFG would be destroyed in the flare. As discussed above (section 3.1), the extraction system generally did not provide sufficient fuel to operate the FP250. At times, it was possible for the FP250 fuel delivery system to cause a back flow of ambient air through the flare. This was remedied by installing an air actuated valve downstream of the LFG takeoff tee which is closed when the FP250 is operating. Mid-way through the demonstration, it was discovered that the FP250's fuel delivery compressor provided sufficient suction on the extraction system piping and it was unnecessary to operate the extraction system blowers during FP250 operation. From this point forward, the extraction system blowers were shut down (manually) when the FP250 was operating. This also appeared to improve control over the extraction rate resulting in a more consistent quality LFG supply to the FP250.

Figure 8 is a schematic diagram of the FP250 system and the existing LFG collection/flare system. Figure 8 shows the location of each measurement that was made in support of quantitative determination of the demonstration's performance objectives. Details on instrumentation and data collection are given below (section 4.4.4).

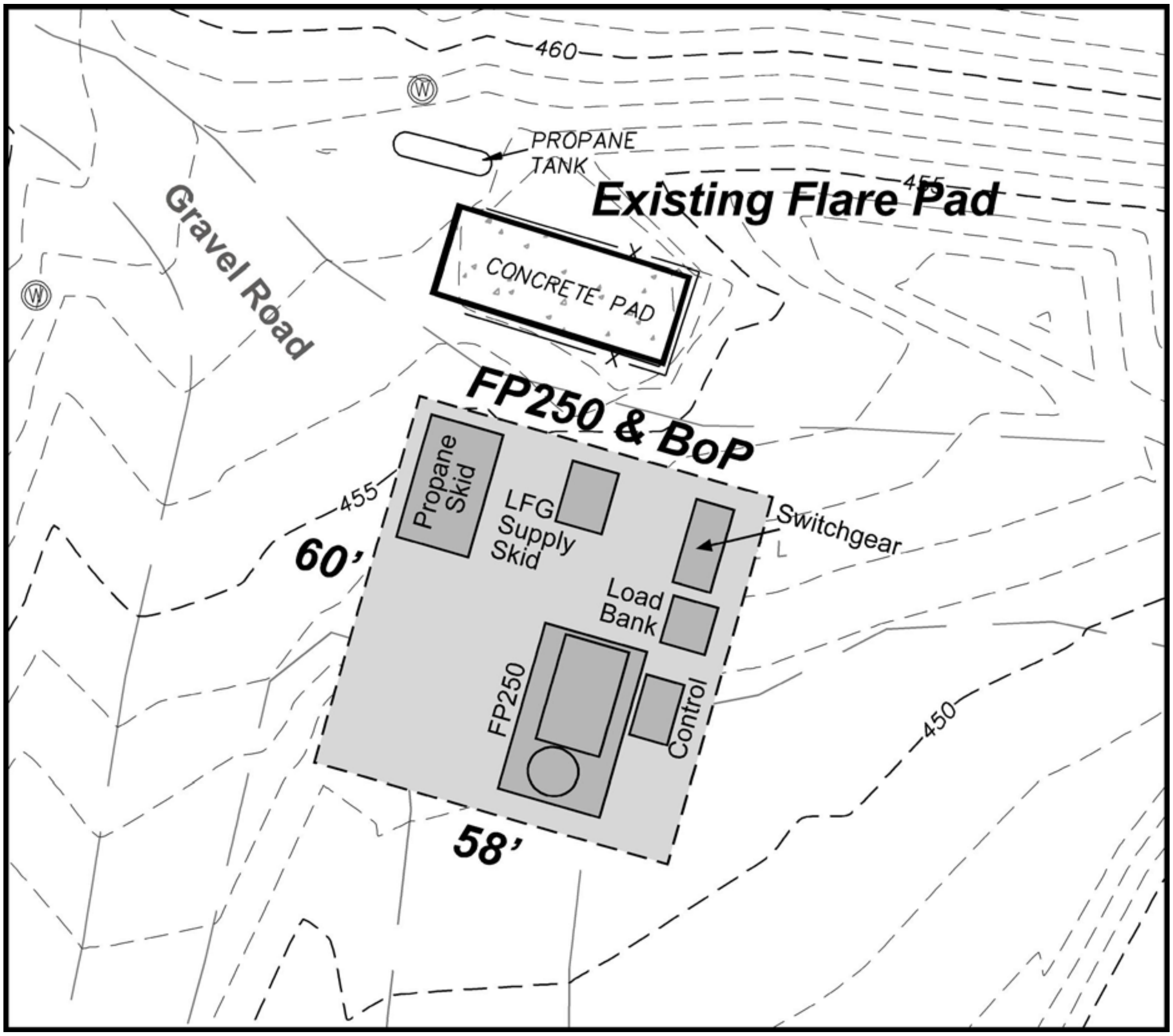

Figure 7. FP250 Site Plan (schematic)

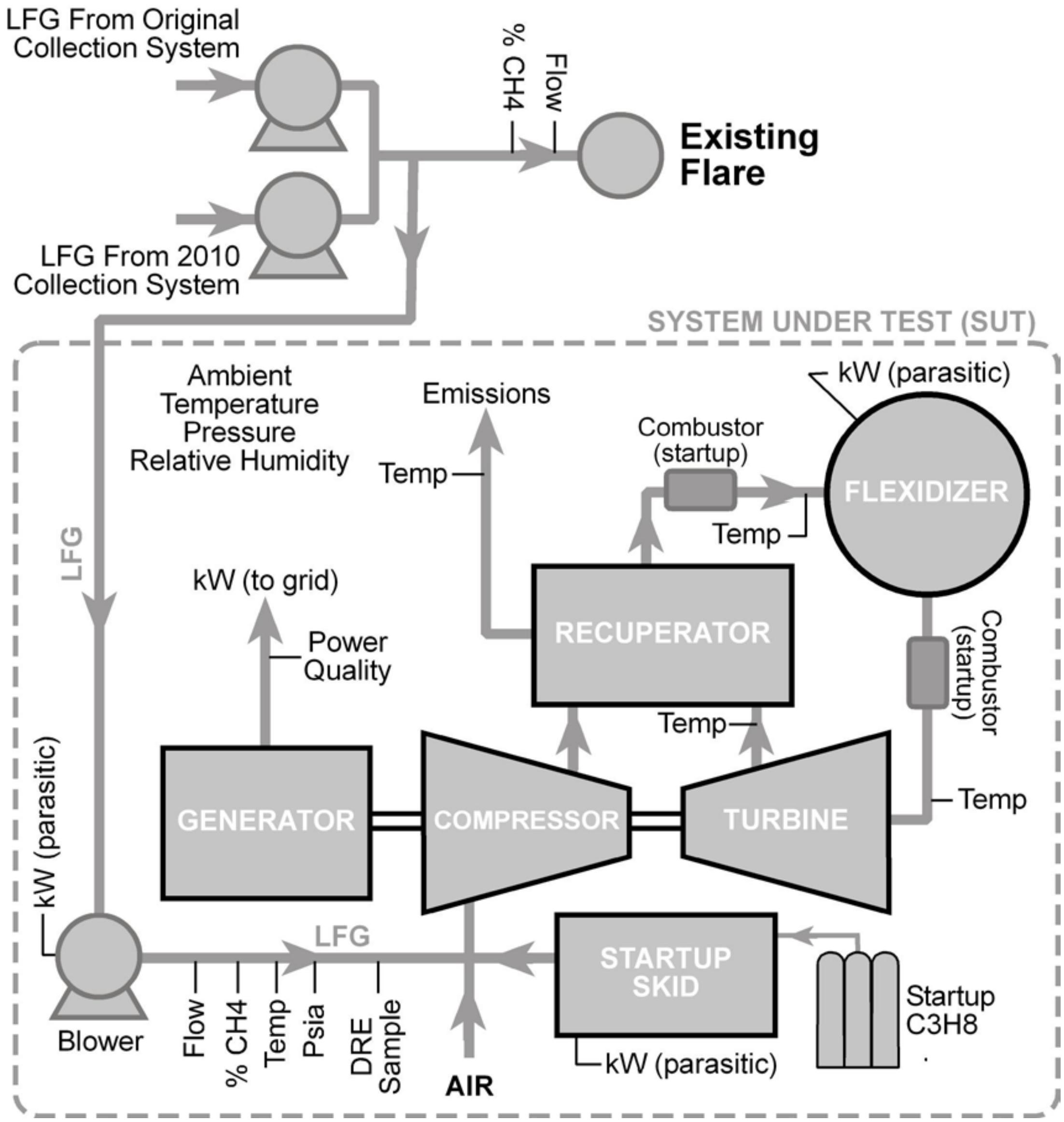

Figure 8. FP250 Monitoring Schematic

4.3.1 HazOp Review

Prior to construction, Southern and Ener-Core conducted a hazard and operability (HazOp) review of the system design. HazOp reviews incorporate elements of failure mode and effects analysis and are the usual format for design reviews conducted by Southern. The review was conducted on January 24-25 2011. The results are summarized below.

For the purpose of the HazOp, the FP250 and balance of plant was divided into the following nodes:

- Node 1: LFG Supply - from flare supply line downstream of extraction system blowers to air/LFG mixing plenum.
- Node 2: Startup System - from propane storage tank to burners (combustor and warmer)

- Node 3: FlexEnergy MT250 EX Turbine
- Node 4: Gradual Oxidizer – from compressor and returning to turbine, with additional review of combustor and warmer operation in this context.

A full review was conducted on all nodes except for the turbine (node 3). The turbine is a field proven component, so only modifications specific to this application were reviewed. Automatic/remote operation of the system was not addressed during the review as this capability was not yet implemented at the time of the review.

Risk ratings for all deviations from design intent identified during the review were 'Acceptable' or 'Acceptable with Control'. Existing safeguards are detailed in the HazOp data sheet maintained in project files.

The following major action items were identified during the review. Minor action items are documented in the data sheet.

- Ener-Core reviewed whether the methane concentration at the turbine air/fuel mixing plenum can exceed the lower explosive limit (LEL). There is no LEL sensor in the plenum. On 1/26/11, Ener-Core reported that maximum LFG flow through the fuel control valve (FCV110) when fully open cannot exceed the LEL in the air plenum.

- Ener-Core reviewed whether flame detectors on the startup system duct burners (E401 warmer and combustor) were required to meet code. Ener-Core documented that the system in place complies with the definition of a Flame Detector in NFPA 85 3.3.65.

4.4 OPERATIONAL TESTING

The following sections describe each operational phase of the FP250 performance assessment. These phases included acceptance testing, system installation and commissioning, steady state operations, and emissions testing. In order to provide a clear overview of the project, a project narrative and timeline of significant events is provided at the head of these sections.

Due to the undersupply of LFG from the landfill, Southern conducted an extensive investigation of the landfill and LFG extraction system to determine whether sufficient fuel to fully operate the FP250 could be obtained from the landfill alone. The results of this investigation are presented in section 3.1.1 above.

Formally, the demonstration objectives are concerned only with steady state operations and emissions testing; however, Southern documented the acceptance testing and commissioning phases to capture information relevant to understanding FP250 performance.

4.4.1 Operational Narrative and Timeline

The FP250 design represented a scale-up and turbine manufacturer change from Ener-Core's 100 kW pilot unit installed and operated at a landfill in Lamb Canyon, CA (see section 2.1). In order to verify the performance of the scaled-up oxidizer and verify engine and controls modifications necessary to integrate the scaled up oxidizer with the 250 kW turbine, Ener-Core installed and operated a test unit at the Alturdyne turbine packaging facility near San Diego, California. The testing and modifications took place between Sept. 2010 and April 2011. Southern was on site in late March 2011 to witness and document acceptance testing of the newly integrated system (see section 4.4.2 below).

In early February 2011, Southern and Ener-Core met with all project stakeholders at Ft. Benning to work out construction details including site preparation, permitting, utility interconnection, etc. Draft site plan and electrical, mechanical, civil and structural drawings and details were shared with Ft. Benning staff. Southern began work on permitting activities with Ft. Benning staff (see section 3.3).

Site preparation and installation activities at the 1st Division Road landfill began in April 2011 and continued through early July 2011. During this time Southern installed monitoring and data acquisition equipment on site to collect and provide remote access to data collected in support of the demonstration. The FP250 was first run on July 12, 2011. Commissioning and shakedown activities continued through September 2011. Details are given in section 4.4.3 below.

The FP250 was officially deemed fully commissioned and ready for continuous operation by Ener-Core on Sept. 29, 2011. A ribbon cutting ceremony was held at the 1st Division Rd landfill on November 8, 2011.

On November 9, 2011, the FP250 was shut down for inspection and maintenance. Abnormal wear on the turbine nozzle and rotor was observed and Ener-Core decided to replace the engine and initiate a root cause analysis to determine the cause of the wear. Engine 1 ran a total of 369.3 hours with 308.8 hours operating in gradual oxidation mode at an average net power output of 208.8 kW. There were 13 start cycles on the engine at the time of replacement.

The results of the root cause analysis were submitted to Southern on January 10, 2012 [7]. The root cause of the turbine wear was determined to be media from the gradual oxidizer entering the turbine section of the engine and eroding the nozzle and turbine rotor. Ener-Core consulted with a turbine erosion specialist and university researchers to investigate whether changes in turbine and nozzle material or coatings could prevent wear. No changes were recommended. Ener-Core also evaluated options for preventing particulate from originating in the oxidizer media, but did not elect to make any changes to the media in the Ft. Benning unit. Ener-Core relocated the dump valves on the Ft. Benning unit to prevent debris from back flowing into the compressor during shutdown and improved shutdown control logic to minimize the use of the dump valves.

Ener-Core also initiated an effort to improve filtration between the oxidizer and the turbine. Two interim ‘drop-in’ filter solutions were installed in the spring and summer of 2012, and a third solution was installed in September 2012. A complete history and discussion of the filtration issue is given in section 6.1.

Engine 2 was installed in early February 2012 and first ran on Feb 22. Engine 2 logged a total of 1710.3 oxidation mode run hours with an average net power output of 189.9 kW, before being taken out of service in July 2012 for the planned install of the new design ‘G3’ engine.

The G3 design incorporates turbine cooling system modifications to reduce or eliminate the passage of aspirated fuel/air mixture around the oxidizer and into the turbine exhaust stream. This is necessary to achieve the ultra-low atmospheric emissions that the FP250 is potentially capable of. Engine 3 logged a total of 1862.8 oxidation mode run hours at an average run-mode net power output of 211.2 kW before it was shut down on November 18, 2012 pending completion of system handover negotiations.

A fully EPA-compliant emissions test on the G3 engine was completed on October 17, 2012 (see section 4.4.5).

The project participants (Southern, Ener-Core and Ft. Benning) initiated handover discussions during the fall of 2012. Operations and maintenance manuals and annual and variable-period maintenance cost estimates were requested from Ener-Core and delivered to the Ft. Benning energy manager so that an O&M contract could be developed and sent out for bid. Ener-Core submitted recommendations and costs for system updates to be completed before system handover. It has remained Ft. Benning's stated intention to continue operation of the plant so long as this can be accomplished on a revenue-neutral basis.

A detailed project timeline providing dates for all significant events during the demonstration program is given in Appendix B.

4.4.2 Acceptance Test

During the winter of 2010-11, Ener-Core assembled and tested the 250 kW system at Alturdyne's engine packaging facility in El Cajon, California. The purpose of the test system was to finalize controls integration with the turbine and to conduct performance testing on the full scale oxidizer/turbine unit. The overall goal of the test was to achieve 200 kW output using dilute natural gas and to confirm emissions meet CARB DG standards [8]. The testing also verified that operating conditions were within expected ranges (e.g., heat input, temps, flows, pressures), and that controls functioned within specifications, including response to subsystem failure (e.g., fuel supply outage).

Southern was on site on March 25, 2011 to observe and document acceptance testing activities. Southern observed as the Alturdyne test unit started up and successfully transitioned to oxidation mode. Power output was higher than expected at 270 kW gross. The system recovered without intervention from a 3 minute fuel supply outage. The system was then shut down and a warm restart was attempted, but a resistor bank failed on the generator braking resistor preventing restart. The system was operated manually during the test. Controls automate was not complete at the time of the test.

Figure 9 shows performance data collected during the acceptance test. Figure 10 shows the system installed at Alturdyne. The system achieved oxidation mode operation (running on aspirated fuel only) after a 3 hour warm up with the combustor and warmer burners firing (minute 180 of the test). The fuel supply was shut off completely for three minutes just before minute 300 of the test. Oxidizer inlet and outlet temperatures and power output dropped off when the fuel was shut off, but the unit continued to generate power using the residual heat in the oxidizer. Once the fuel supply was restarted, the system resumed operation without operator intervention.

Ener-Core personnel measured emissions from the turbine exhaust and oxidizer outlet after stable operation was achieved in oxidation mode. Concentrations of nitrogen oxides (NO_x) and carbon monoxide (CO) were measured with a LAND Lancom III model emissions analyzer and documented on print outs directly from the analyzer. A total of two sets of emissions measurements were completed at the turbine exhaust and three sets were completed at the oxidizer outlet during the test. Two sets of ambient measurements were also completed in order to determine net emissions since ambient levels of NO_x and CO were somewhat elevated in the test yard due to the engine operation.

Net NO_x emissions at both the oxidizer outlet and the turbine exhaust were within +/- 15% of one ppm, which equates to 0.027 lb/hr (assuming 3500 dscfm exhaust flow). On a pound per hour basis, the CARB DG 2013 standard for NO_x is 0.015 lb/hr (assuming 210 kW net output, which is representative of average performance for the Ft. Benning demonstration unit). Thus, NO_x emissions for the test unit somewhat exceeded the CARB DG 2013 standard, but readily meet the CARB DG 2003/8 standard (0.1 lb/hr) and were also better than EPA AP42 typical emissions for best control technology (enclosed flare at 0.117 lb/hr) [9].

CO emissions measured at the oxidizer outlet were zero. At the turbine exhaust, however, CO concentrations averaging 126.75 ppm (or 1.9 lb/hr) were measured. Thus, CO emissions exceeded the CARB DG 2003/8 and 2013 standards (1.2 and 0.021 lb/hr respectively). Although the oxidizer completely destroys CO, a portion of the aspirated methane fuel bypasses the oxidizer due to the design of the cooling system in the turbine and is partially oxidized to CO as it passes over hot surfaces en-route to the turbine exhaust stack. This 'leak path' was a known issue at the time of the acceptance test and Ener-Core was in the process of engineering modifications to the turbine cooling system to avoid excess CO emissions. These modifications were ultimately implemented in the G3 engine design installed at Ft. Benning In July 2012.

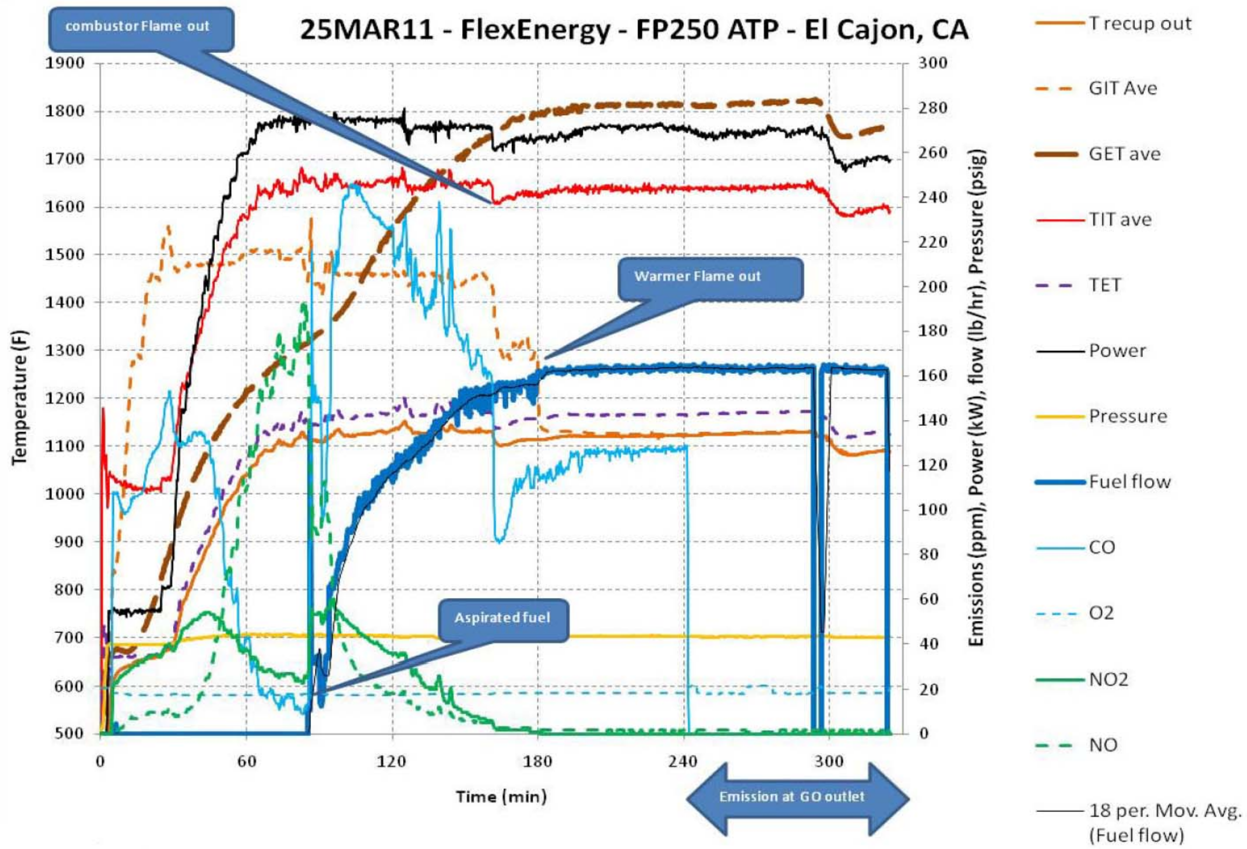

Figure 9. FP250 Acceptance Test Operational Data

Figure 10. Alturdyne Acceptance Test System

4.4.3 Commissioning

Commissioning activities took place at Ft. Benning between July and September 2011. The FP250 first ran on July 12, 2011 and Ener-Core officially deemed the system fully commissioned and ready for continuous operation on September 29, 2011. However, as described above (section 4.4.1), Ener-Core continued to modify and improve the system throughout the demonstration period.

Throughout the commissioning period, Southern monitored operational data remotely and reported status and issued follow up questions to Ener-Core and other project participants on a weekly basis. Significant events were logged as they occurred. Southern was on site to observe commissioning activities on July 28 and August 18, 2011.

Commissioning activities included verifying proper operation of all subsystems and checkout and optimization of controls for integrated system operations. Controls optimization included optimization of the startup sequence, temperature ramp rate, and transition temperature to oxidation mode.

On July 29, while attempting to start the system, excess propane accumulated in the combustor due to intermittent operation of the igniter resulting in a 'hot start' that damaged the recuperator. The recuperator was replaced and the unit was back in service by August 14. Software changes were made to prevent recurrence of a hot start and there were no further occurrences of this issue throughout the demonstration. Beginning on September 15, problems were encountered with the auxiliary compressors on the turbine engine that provide engine cooling and sealing. These problems were resolved by September 29.

4.4.4 Operations Monitoring

Southern's monitoring and data acquisition system became operational on July 5, 2011 – five days prior to the first FP250 run. Southern was able to remotely monitor FP250 operations via a cell router. Data were stored at a 10 minute collection interval, which provided sufficient resolution to detect minor changes in operation. Data were downloaded and reviewed on a weekly basis and Southern prepared and submitted a weekly status update to all project participants.

Whenever the system shut down, Southern requested an explanation of the cause for the shutdown and Ener-Core would typically respond within one to two business days. Southern logged all downtime and assigned a downtime classification in accordance with ANSI Std.762[10] to allow quantitative determination of system availability and reliability. The cause of the down time was noted for each shut down.

Southern continued monitoring and updates through November 18, 2012 when Ener-Core elected to cease operations at Ft. Benning pending system handover. During this period, continuous monitoring of gross and net power output were conducted, along with monitoring of heat input (LFG flow and methane concentration delivered to the FP250), FP250 system 'health' parameters, landfill gas extraction system parameters, and ambient conditions, as shown in Figure 8 (in section 4.3). Table 3 and Table 4 give instrument specifications for Southern and Ener-Core sensors, respectively. Data from Ener-Core sensors was used primarily as an indicator of system status and to aid screening of results so that steady state operation is accurately represented in the data analyses. Ener-Core's LFG flow data were also logged as a backup to Southern's LFG flow measurement. Southern's flow meter turned out to be unreliable.

Parasitic electrical loads are loads required for FP250 operation that net against the gross power output. The wiring for the FP250 system was configured such that all parasitic loads could be measured together from a single 3-phase 480V 4-wire Wye bus with a single power meter. The gross generator output from the FP250 was measured by a separate power meter. A bi-directional power meter was also installed at the utility interconnect.

Figure 11 shows the installed configuration of Southern's instrumentation. Southern's instruments were installed in a spool piece fitted with a bypass so that the FP250 could continue to operate in the event that Southern's sensors required service while the system was online.

Propane consumed for FP250 system startup was recorded by Ener-Core and reported to Southern on a monthly basis starting in July 2011. Ener-Core began reporting propane use for fuel augmentation in February 2012. Propane usage was measured with a calibrated orifice flow element and differential pressure transmitter.

Southern obtained flow and methane concentration data for the flare feed, as well as monthly well head data for the LFG extraction system. These data were used to monitor the status of the LFG extraction system and characterize the LFG supply. The wellhead data were obtained monthly from the USACE via their contractor, J2 Engineering. The monthly data consisted of measurements at each wellhead of LFG flow and concentrations of methane, carbon dioxide and oxygen, as well as concentration at the flare inlet using a portable LandTec GEM2000 landfill gas meter.

The LFG flow to the flare was measured via a pre-existing pitot tube located downstream of the FP250 takeoff, indicating net flow to the flare when the FP250 is operating. Southern received daily reports of LFG flow via the flare's Telemetrix monitoring system, however these data were of limited usefulness. The flow calibration was imprecise and in most cases there was no net flow to the flare when the FP250 was operating.

Ener-Core's on site technician also made daily measurements of methane concentration at the flare feed when the FP250 was operating. These data were forwarded to Southern on a daily basis. Since there was no excess LFG to the flare, the LFG flow measurements downstream of the FP250 fuel supply skid provided an accurate measurement of the total LFG flow. These data were ultimately used to characterize the LFG extraction system performance as reported in section 3.1 above.

Table 3. Instrument Specifications for Continuous Monitoring

Measurement	Required for:	Tag	Units	Nominal	Low	High	Accuracy	Output	Power	Mfg	Model
LFG Volume Flow to FP250	Heat Input to FP250	LFG_Flex	cfm	120	24	340	2% of reading	4-20 mA	24VDC 1A	Air Monitor Corporation	LO-flo/SS Pitot Traverse Station Model FR (4 inch flange to 3 inch station) with VELTRON DPT-plus transmitter
LFG Methane Concentration to FP250	Heat Input to FP250	CH4_Flex	%	45	0	100	0.2% FS	4-20 mA	24VDC 1A	BlueSens	BCP-CH4
LFG Temperature to FP250	Temperature corrections for flow and CH4 concentration	Temp_Flex	deg F	65	0	120	0.2 deg F	4-20 mA	24VDC 1A	Omega	PR18-2-100-1/4-6
Gross Power (Bi-directional)	Power Production	PM_Gross	kW	200	0	250	1% of reading	pulse to 4 Hz	none	Wattnode	WNB-3Y-480-P
Total Parasitic Load	Net Power Production	PM_Par	kW	30	0	120	1% of reading	pulse to 4 Hz	none	Wattnode	WNB-3Y-480-P
Ambient Temperature	Performance relative to ambient conditions	Temp_Amb	deg F	85	0	120	1 deg F	4-20 mA	6 to 24 Vdc	Omega	HX94AC
Ambient Pressure	Performance relative to ambient conditions	Pres_Amb	in Hg	26	30	32	1% FS	4-20 mA	10 to 30 Vdc @ 10 mA	Omega	PX429-26BI
Ambient Relative Humidity	Performance relative to ambient conditions	RH_Amb	%	60	0	100	2.5% RH	4-20 mA	6 to 24 Vdc	Omega	HX94AC

Table 4. Supplementary Data Acquired from Integral FP250 Sensors

Measurement	Required for:	Tag	Units
LFG Flow	FP250 operation + cross check on SRI sensor	LFG_Flex2	cfm
LFG Methane Concentration	FP250 operation + cross check on SRI sensor	CH4_Flex2	%
Bi-directional Power	FP250 operation + cross check on SRI sensor	BPW_Flex	kW
Oxidizer Inlet Temp	FP250 system 'health' indication	TT_GIT	deg F
Oxidizer Outlet Temp	FP250 system 'health' indication	TT_GET	deg F
Turbine Exit Temp	FP250 system 'health' indication	TT_TET	deg F
Recuperator Exhaust Temp	FP250 system 'health' indication + heat recovery estimates	TT_EGT	deg F

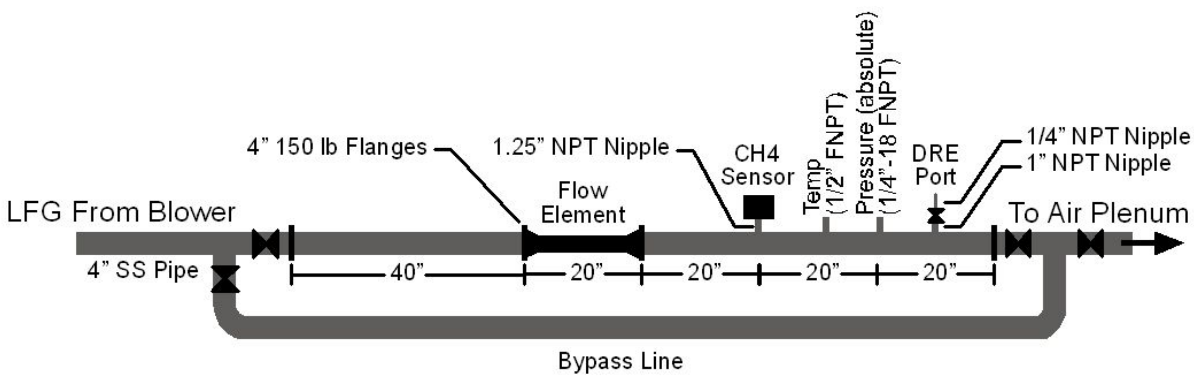

Figure 11: LFG Measurement Configuration Detail

4.4.5 Emissions and Destruction Efficiency Testing

In order to capture representative data, atmospheric emissions and NMOC destruction efficiency measurements were planned for when the engine had accumulated 1,000 hours of operation. At Ener-Core's request, the emissions test was delayed until the new design 'G3' engine version was installed and had accumulated 1000 hours of operation. The 'G3' engine was designed to minimize 'leak paths' that allow a small portion of the aspirated fuel/air mixture to bypass the oxidizer and exit the turbine exhaust. This results in excess carbon monoxide emissions as a result of partial oxidation of the methane fuel over hot surfaces within the engine.

The emission testing was completed on October 17, 2012 by Integrity Air Monitoring, Inc. (Integrity Air). Integrity Air is a fully certified emissions testing contractor and has performed satisfactorily on previous demonstration and verification projects for Southern Research. At the time of the test, the 'G3' engine had accumulated 1276 oxidation mode run hours. The test was a fully rigorous compliance test using standard EPA compliance test methods (see Table 5 below). Three 1-hour test runs were conducted to determine mass emissions (lb/hr) of the pollutants listed in Table 5.

To comply with EPA methods, the exhaust stack was fitted with two sampling ports (4 inch ID open ports) located at the same elevation on the stack at 90 degrees to each other. The ports were located a minimum of two stack diameters downstream of any obstruction to flow and one half diameter upstream of the exhaust. The stack was fitted with angle iron brackets and eyebolts to support the sampling trains.

Destruction Efficiency

Determination of NMOC destruction efficiency was made based on concurrent concentration and flow measurements at the inlet and exhaust of the FP250.

Southern's experience with compliance testing and the experience of Integrity Air indicates that, to conform with commonly accepted practice, the DRE inlet sampling location would be in the diluted gas stream - downstream of where the LFG feed gas and dilution air are mixed before entering the FP250 compressor. However, due to the configuration of the inlet air plenum on the IR turbine, it is not possible to obtain a representative flow measurement of the diluted stream. Therefore, the inlet DRE samples were obtained from a port located in the LFG supply line to the FP250 main compressor (see Figure 11) to provide inlet NMOC mass flow with at least as much accuracy as sampling in the diluted stream. South Coast AQMD approved the same method for the regulatory compliance test at Ener-Core's Lamb Canyon pilot plant [11].

The LFG supply line is a 4 inch stainless steel pipe. The sampling port is a 1 inch diameter pipe stub welded to the 4 inch pipe and fitted with a 1 inch ball valve. Downstream of the valve, a ¼ inch male NPT nipple was provided to attach the dilution probe. The flow measurement for the destruction efficiency determination was obtained from Ener-Core's flow element since Southern's flow meter proved to be unreliable.

Table 5. Emissions Test Methods

Parameter	EPA Reference Method
Volumetric Flow	1, 2, 3A & 4
CO_2, SO_2, NO_x, and CO	3A, 6C, 7E & 10 (respectively)
SO_2	16A (Modified to use an SO_2 analyzer in place of wet chemistry/titration)
THC/NMOC	25A & 18 (NMOC as THC less methane)
PM_{10}	OTM-27 and OTM-28

4.5 SAMPLING PROTOCOL

Demonstration data collection began on July 5, 2011 and continued through the end of operations on November 18, 2012. Data for all parameters listed in Table 3 and Table 4 (above) were stored at 10 minute intervals on Southern's DataTaker™ data logger and retrieved via cellular router on a weekly basis.

Raw data were retrieved each week and appended into the 'raw data' tab of Southern's data analysis spreadsheet. To preserve traceability, raw data were never altered in any way. Weekly raw data files as downloaded from the logger were backed up on Southern's server. There were no significant data collection or retrieval issues during the extended monitoring period. Corrected or calculated values were computed from raw data in the 'calc_data' tab of the data analysis spreadsheet. All constants and calibration factors used are stored in the same spreadsheet and referenced by cell label to facilitate traceability and auditability of the results. These calculations and corrections included:

- Conversion of ambient pressure measurements in mm Hg to psia.
- Correction of Southern's flow measurements to standard conditions (1 atm. and 60^{o} F) using pressure and temperature sensor data located in line with the flow meter.
- Correction of LFG temperature measurements based on a calibration curve developed in Southern's laboratory prior to deployment.
- Conversion of logged pulse data from Southern's power meters to kW and kWh.
- Calculation of net kW output as the difference of gross output and parasitic load power measurements.
- Compensation of Southern's methane meter measurements for LFG temperature and pressure. Correction factors were provided by the manufacturer.

The data analysis spreadsheet also includes a complete downtime log and a record of propane usage provided by Ener-Core.

Calculated results were automatically summarized over discrete time periods of interest using Excel database statistical functions. Summary performance data were submitted to project stakeholders each month starting January 2012. For this final report, the time periods of interest correspond to when each of the three engines installed at Ft. Benning were operated.

Additional details of data collection for non-continuous measurements (i.e., propane usage, LFG methane concentrations at the wellheads and flare and causes for down time) are discussed as part of the presentation of operational testing in section 4.4 above.

4.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

The performance of the sensors and data acquisition equipment used to monitor and record the performance of the FP250 at Ft. Benning was more than adequate to provide valid data for assessment of the demonstration's performance objectives. All instruments were calibrated by the manufacturer prior to installation and no recalibrations were required per manufacturer recommendations during the demonstration period. Duplicate measurements of methane concentration and LFG flow were collected.

Southern conducted a calibration of the LFG temperature sensor using hot (180 F), cold (40 F) and room temperature (74F) baths. The calibration curve developed was used to correct the raw temperature readings from the field.

Southern also conducted a 10 point calibration check of the methane meter prior to deployment using an Horiba SGD-7106 Gas Divider (+/- 0.5% rated) using 100% CH4 CP Grade and 100% N2 UHP Grade as the diluent gas. A Fluke 1587 Multimeter was used to measure the milliamp output from the methane meter. Readings from the meter display were also recorded and precisely matched the milliamp output. Methane concentrations were stepped up from 0 to 100 percent in 10% increments and then stepped back down in 10 percent increments. The readings in the middle of the range were 4-6% higher than expected. Upon consultation with the manufacturer, this difference was determined to be the result of not having an equal percentage of methane and carbon dioxide in the calibration gas mixture. The meter is set up specifically to measure landfill or digester gas where roughly equal amounts of methane and carbon dioxide are normally present. At Southern's request, the manufacturer conducted tests on the same model meter with 30% methane, 30% carbon dioxide and 40% nitrogen and achieved results within 0.5%, which is within the specification for the meter. Based on this, it was determined that the methane meter calibration was accurate.

All data were reviewed on a weekly basis by examining time series plots of all collected data values and making comparisons with expected values and previous data collected. Any anomalies in the data were investigated and all issues were documented using comments embedded in the data analysis spreadsheet.

The only data quality issue of significance was the failure of Southern's LFG flow meter to provide representative results. This is discussed in detail in section 4.6.1 below. Ener-Core's methane data were not consistently reliable as the calibration tended to drift or was dependent on sample flow to the meter. This had no impact on data quality since Southern's methane meter performed well throughout the demonstration period.

4.6.1 LFG Flow Measurement Issue

Southern's LFG flow meter failed to provide reliable LFG flow data throughout the demonstration. Flow readings were typically 'in the ballpark' (based on comparison with expected flow, Ener-Core's flow meter, and flow measurements at the flare) but varied considerably even though LFG flow was known to be stable downstream of the FP250's fuel delivery compressor. Southern's flow measurement utilized a differential pressure transmitter paired with a flow element designed with a number of small ports arranged axially and radially on the dynamic and static pressure sides, respectively (see Table 3 above). The ports in the flow element were designed to yield a representative integrated flow across the cross sectional area of the flow element. The differential pressure transmitter was located within 2 feet of the flow element and the pressure tap tubing was arranged to drain downward away from the transmitter. The flow transmitter was calibrated by the manufacturer prior to installation in July 2011 and was calibrated again when the instrument was removed for service in February 2012. The service was necessitated when the FP250's LFG feed lines filled completely with condensate during the extended down time between

November 2011 and February 2012. The condensate level was higher than the flow transmitter, so water filled the impulse lines and entered the transmitter's capillary tubes – necessitating factory service.

Southern worked with the instrument manufacturer to resolve the flow measurement issue; however, the effort was unsuccessful. It was concluded that excess moisture in the LFG tended to restrict the small ports in the flow element resulting in unrepresentative or variable readings. This did not have a significant impact on overall data quality because (1) a backup flow meter was available that provided representative readings and (2), the LFG flow readings were taken primarily as a means to determine the efficiency of the FP250, which was not a primary demonstration objective.

Ener-Core utilized an integrated transmitter and orifice plate manufactured by Rosemount (Model 2051CG2A02A1AS5E5) to determine LFG flow. This meter was mounted immediately downstream of the FP250's LFG delivery compressor and approximately 10 feet upstream of Southern's meter. Southern was unable to obtain a calibration certificate for Ener-Core's flow meter; however, the readings from this meter were stable and consistent with expected values. Readings from Ener-Core's LFG flow meter were logged on Southern's data acquisition equipment, so a complete record is available. Readings from Ener-Core's flow meter were used for efficiency calculations, to estimate the LFG extraction rate and for calculation of NMOC destruction efficiency following the emission test.

4.7 SAMPLING RESULTS

As noted above, collection of 10-minute interval monitoring data began on July 5, 2011 and continued through the end of operations on November 18, 2012. All raw data, calculated results and data summaries are stored on Southern's secure data server and are available upon request.

Table 6 is a performance summary giving operating hours and power generation for periods when each of the three engines installed at Ft. Benning was operating as well as the combined totals for all three engines. Note that the cumulative power and average power outputs are based on run mode hours, which include startup time where power output is ramping up. As there was significant startup time during the demonstration due to frequent restarts, the average power output values are somewhat lower than would be the case in full oxidation mode operation.

Figure 12 through Figure 15 show a representative period of data collected during August 2012. These are examples of the same set of charts that were used for weekly examination of the data. The date range for the charts can be changed dynamically so that any selected period can be examined and one may zoom in to examine a particular event or zoom out to examine trends. Instrument tags referred to in the charts are defined in Table 3 and Table 4 (above).

Table 6. FP250 Performance Summary

Engine 1 Performance Summary		
Start Date	7/12/11 0:00	
End Date	11/10/11 0:00	
Available Hours	2904	hours
Cumulative Run Mode Hours	369.3	hours
Cumulative Flex Mode Hours (Service Hours)	308.8	hours
Cumulative Time during Startups	60.5	hours
% of available hours in Flex mode	10.6%	percent
Total Number of startups	13	
Cumulative Gross Generated (SRI)	82.8	MWh
Cumulative Net Generated (SRI)	78.2	MWh
Average Net Power Output During Operation	211.8	kW
Engine 2 Performance Summary		
Start Date	2/22/12 0:00	
End Date	7/8/12 0:00	
Available Hours	3,288	hours
Cumulative Run Mode Hours	1822.3	hours
Cumulative Flex Mode Hours (Service Hours)	1710.3	hours
Cumulative Time during Startups	112.0	hours
% of available hours in Flex mode	52.0%	percent
Total Number of startups	18	
Cumulative Gross Generated (SRI)	365.4	MWh
Cumulative Net Generated (SRI)	355.8	MWh
Average Net Power Output During Operation	195.3	kW
Engine 3 Performance Summary		
Start Date	7/23/12 0:00	
End Date	11/19/12 0:00	
Available Hours	2,856	hours
Cumulative Run Mode Hours	1980.2	hours
Cumulative Flex Mode Hours (Service Hours)	1862.8	hours
Cumulative Time during Startups	117.3	hours
% of available hours in Flex mode	65.2%	percent
Total Number of startups	24	
Cumulative Gross Generated (SRI)	434.2	MWh
Cumulative Net Generated (SRI)	426.1	MWh
Average Net Power Output During Operation	215.2	kW
Combined Performance Summary (Engines 1, 2 and 3)		
Available Hours	9,048	hours
Cumulative Run Mode Hours	4171.8	hours
Cumulative Flex Mode Hours (Service Hours)	3882.0	hours
Cumulative Time during Startups	289.8	hours
% of available hours in Flex mode	42.9%	percent
Total Number of startups	55	
Cumulative Gross Generated (SRI)	882.4	MWh
Cumulative Net Generated (SRI)	860.2	MWh
Average Net Power Output During Operation	206.2	kW

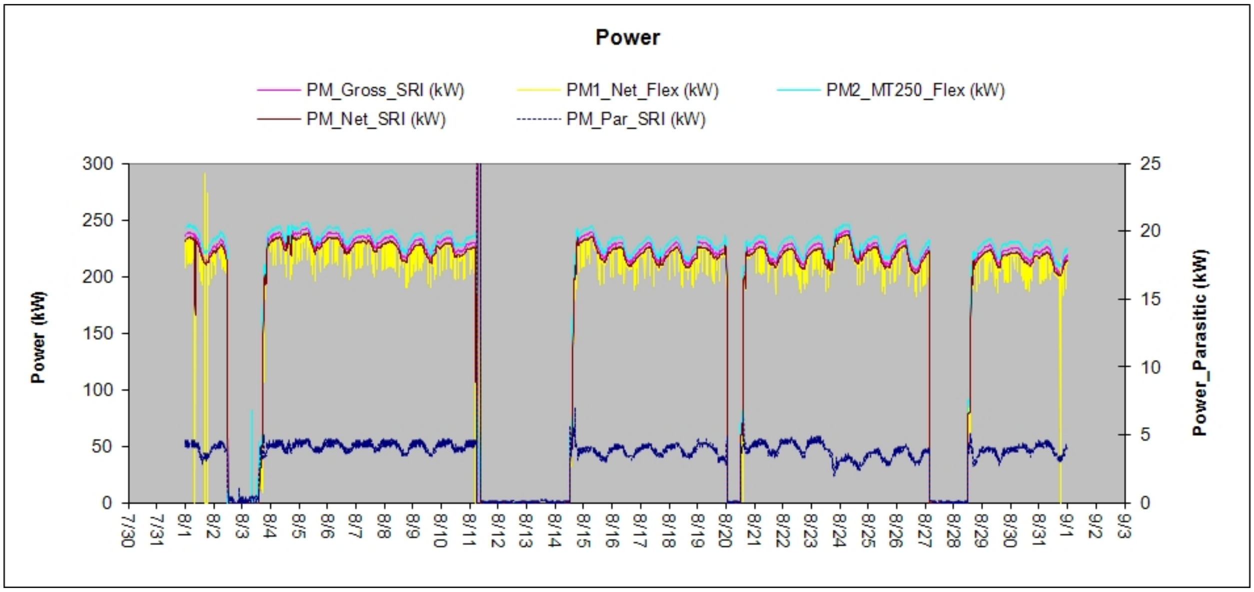

Figure 12. Typical FP250 Power Generation and Parasitic Loads Plot

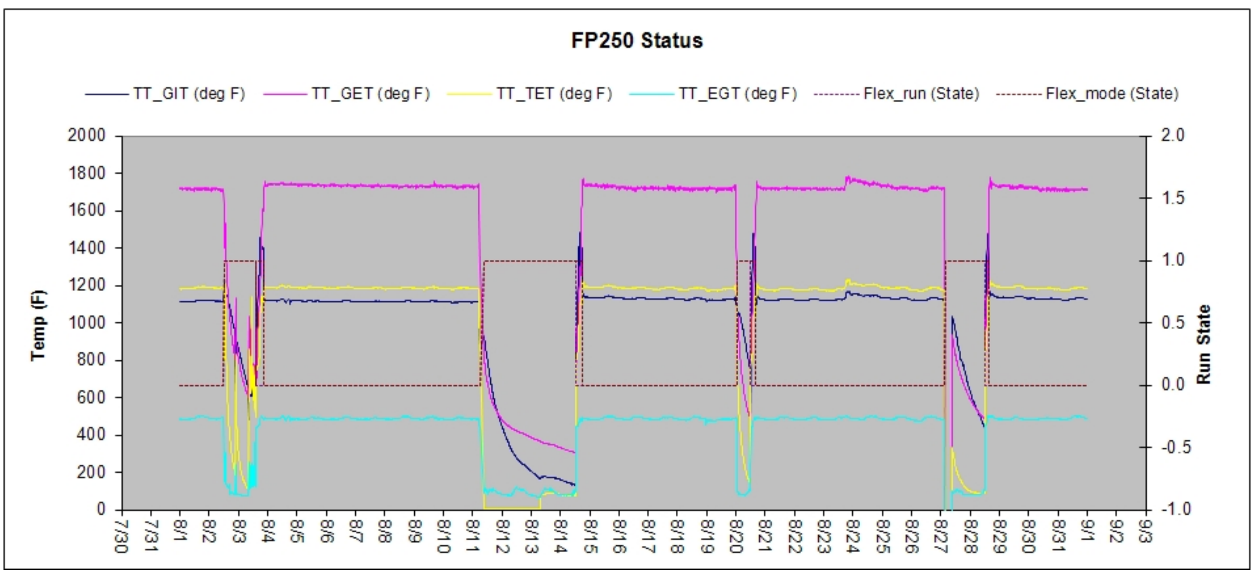

Figure 13. Typical FP250 Run Status Plot

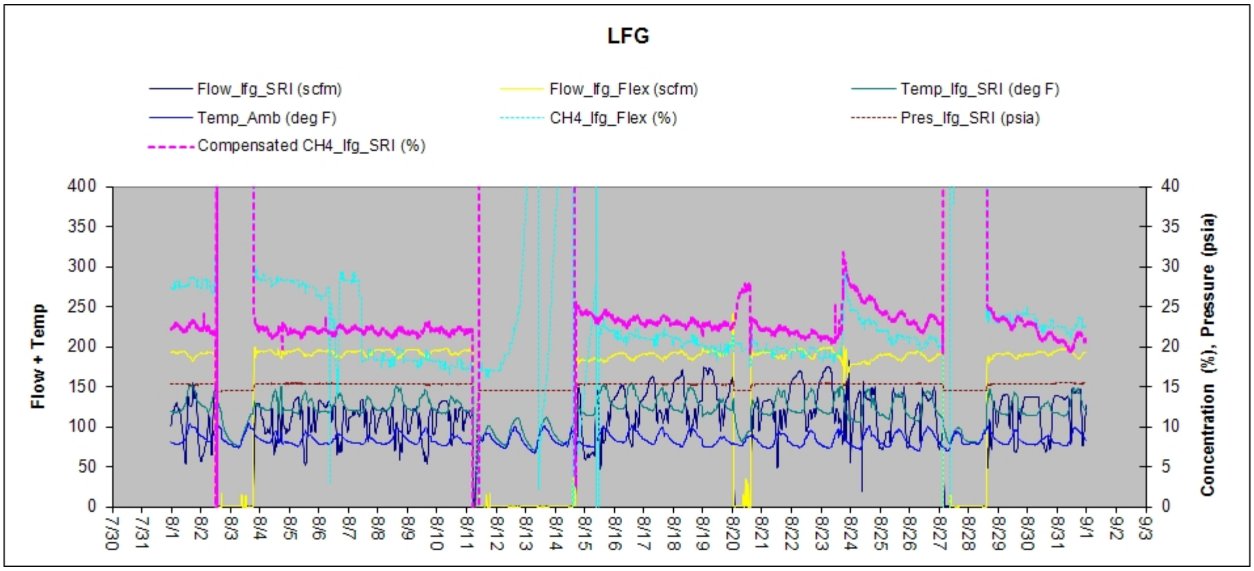

Figure 14. Typical LFG Conditions Plot

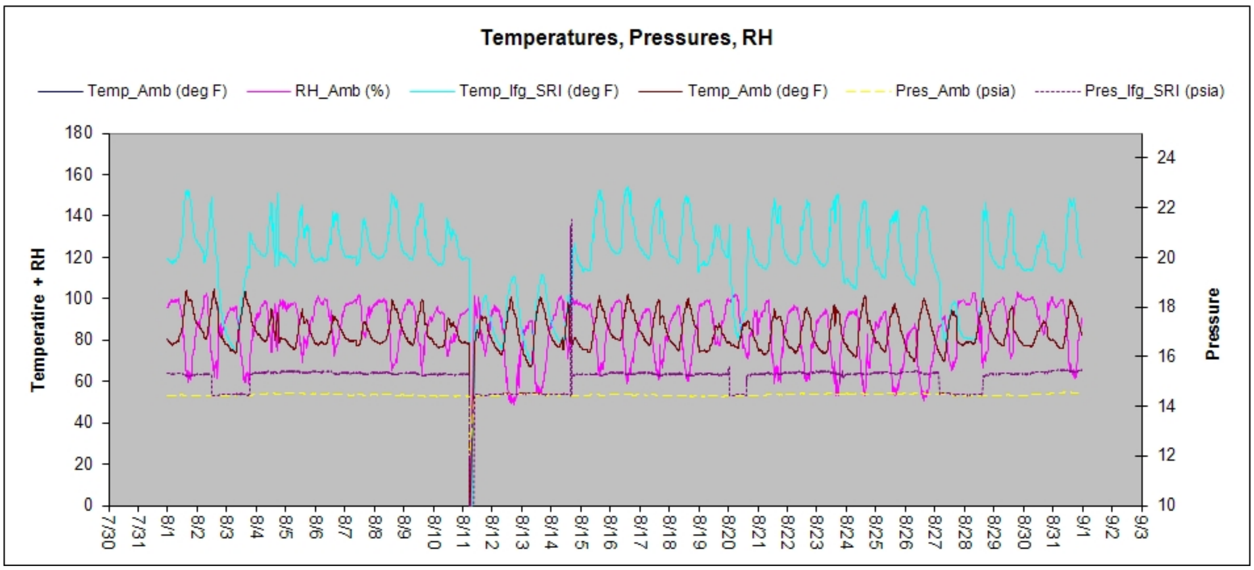

Figure 15. Typical Ambient and LFG Conditions Plot

5.0 PERFORMANCE RESULTS

The results of the demonstration for each performance objective are presented in summary and in detail below. The methods employed to verify each demonstration objective are presented in section 4.0 above and further detail is available in the demonstration plan. The objectives related to energy production, reliability and operability address energy security at DoD installations. The economic assessment objective addresses DoD energy cost reductions. Installation greenhouse gas reductions and other environmental benefits are addressed by way of the objectives related to emissions measurements, destruction efficiency and determination of greenhouse gas reductions.

5.1 SUMMARY OF PERFORMANCE OBJECTIVES AND OUTCOMES

Table 7 summarizes the performance results for each demonstration plan objective. The following section (section 5.2) provides a detailed discussion for each result.

Table 7. Performance Results

Objective	Metric	Success Criteria	Result
Energy: Verify power production & quality.	Net real power delivered (kWh);	Nominal 200 kW gross continuous (1750 MWh/yr) less temperature dependent derating (to be established). Power quality meets utility inter-connection requirements	Objective met. Average net real power generation of 220 kW during gradual oxidation mode operation with G3 engine design.
Emissions: Verify emissions meet regulatory requirements and are lower than best alternate LFG emissions control technology.	lb/hr, lb/MWh or ppm emitted	Emissions meet or exceed CARB 2013 requirements for distributed generation and host site air permit requirements. Emissions are lower than EPA AP42 typical values for best alternate LFG control technology (boiler/steam turbine).	Objective met for NOx and NMOC. CO emissions from the turbine exhaust do not meet the objective; however, CO emissions measured at the oxidizer outlet do meet the objective.
Emissions: Verify NMOC destruction efficiency	Percent destruction efficiency for NMOC.	Destruction efficiency exceeds EPA AP42 typical value for enclosed flare (97.7%) and meets AP42 value for Boiler/Steam Turbine (98.6%).	Destruction efficiency meets the objective at 99.6%.
Emissions: Verify greenhouse gas emissions reductions.	Metric tons CO_2e/yr reduction relative to site specific baseline conditions	Greater than 800 metric tons CO2e avoided emissions due to power generation (above baseline). Greater than 6000 metric tons CO2e reduction due to destruction of CH4. Greater than 10% increase in GHG reduction compared to flare only.	Objectives met without consideration of GHG emissions due to supplemental propane use. Objectives nearly met when propane use is considered.
Assess economic performance	Simple payback (years), NPV ($)	Simple payback < 5 years; Positive NPV.	Objective not met at the current grid electricity price at Ft. Benning ($0.069/kWh). A 5 year payback is achieved at a grid electricity price of $0.18/kWh, and a positive NPV is reached at $0.10/kWh.
Determine system availability/reliability and operating impacts.	Percent availability/reliability, plus descriptive narrative.	Availability exceeds 95%. Reliability exceeds 97%. Operability is acceptable to operating authority.	Availability was 57% and reliability was 82%. Availability net of forced and planned outages was 76%.

5.2 PERFORMANCE RESULTS DISCUSSION

The following sub-sections present and discuss the demonstration results for each performance objective.

5.2.1 Energy: Verify Power Production

The success criterion for this objective was to generate 200 kW gross output during operations. The FP250 exceeded this goal generating an average of 211.5 gross kW power output based on total run-mode operating hours and cumulative power output by all three engines installed at Ft. Benning during the demonstration period. Net power output averaged 206.2 kW. Net power output is the difference between gross power output and the parasitic loads. The parasitic load includes the power required to run the LFG supply compressor, controls, oxidizer heater banks and auxiliary loads. All parasitic loads were wired through a single bus so that only a single power measurement was required to capture the total parasitic load.

Parasitic loads averaged 12.4 kW for engine 1, 5.3 kW for engine 2 and 4.1 kW for engine 3. The reduced parasitic loads for engine 2 and 3 are due to a reduction or elimination of the use of electric heaters installed in the gradual oxidizer to assist in startup and achieving stable operations. With greater operating experience, it was determined that the use of these heaters is unnecessary.

Table 6 (above) summarizes performance results for each of the three engines installed at Ft. Benning during the demonstration. The performance of Engine 3 was improved over the first two engines installed, with Engine 3 net power generation of 215.2 kW averaged over all operating run-mode hours including startup periods. During full oxidation-mode operation, engine 3 produced an average net power output of 220 kW. Southern considers that the 220 kW net power output value will reflect the performance of future installations and this value is used in the economic assessment.

At 90% availability, cumulative net power output is expected to amount to 1,735 MWh per year. Actual availability achieved during the demonstration is discussed in section 5.2.6 below.

Interconnection with the distribution grid operated by Flint Energy was successful.

Generating Efficiency

The data requirements to determine electrical efficiency include net power output and total heat input. Heat input from LFG (BTU/hr) was determined from LFG flow and methane concentration measurements at the FP250 fuel supply header. As discussed above (section 3.1.1), heat input in addition to that supplied by the LFG was necessary to operate the FP250 and was provided by augmenting the LFG supply with propane. Heat input from propane augmentation was determined from daily summations of propane usage provided by Ener-Core.

To calculate efficiency, the net electrical output (in units of Btu/hr) is divided by the total heat input (in Btu/hr) from LFG/methane and supplemental propane. The net electrical output (in kW) is converted to Btu/hr applying a factor of 3412.14 Btu/hr per kW. The heat input from methane was calculated from the percentage methane concentration in the LFG, the LFG flow rate (scfm), and the higher heating value (HHV) of methane (1012 Btu/scf). The heat input from propane was calculated from the daily propane usage for augmentation (gallons), and the heat content per gallon of propane (91,600 Btu/gallon).

For engine 2 (installed Jan/Feb 2012), the total heat input was 3.4 MMBtu/hr on average. Average net efficiency for Engine 2 was 19.7% (HHV basis). For engine 3 (installed July 2012), the average heat input was 3.2 MMBtu/hr. Average net efficiency for engine 3 averaged 23.2% (HHV basis). It was not possible to calculate efficiency for Engine 1 as propane usage data did not become available until Engine 2 was installed.

The electrical efficiency was expected to be approximately 22% or 15,500 BTU/kWh (based on manufacturer specifications and estimated parasitic loads). At standard ISO conditions (59F at sea level), Ener-Core estimates the efficiency at 26% on an LHV basis. Higher heating value (HHV) efficiencies are given in this report consistent with the EPA/ETV DG-CHP protocol; however lower heating value (LHV) efficiencies, which are somewhat higher, are often reported in industry literature.

Propane augmentation in terms of heat input averaged 26.4% for Engine 2 (using data from May - June 2012) and 19.7% for Engine 3 (using data from July-Oct 2012).

Heat Recovery

To estimate heat recovery potential, exhaust gas temperature and mass flow were measured during the emissions test conducted on October 17, 2012 and compared to the characteristic specification (per Flex Energy specifications) for the FP250 heat recovery unit.

The measured exhaust gas flow (wet basis) was 4,028 scfm and the exhaust gas temperature was 491.8 ºF. The molecular weight of the exhaust gas (wet basis) was 28.7 lb/lb mol. These values represent the average over the three, 1-hour test runs. These figures yield an exhaust gas mass flow of 304.7 lb/min.

Heat recovery is a function of exhaust gas mass flow and temperature as well as the heat recovery fluid inlet temperature and flow. Ener-Core gives heat recovery estimates (see Figure 16 below) based on a characteristic specification of exhaust gas mass flow of 282 lb/min at a temperature of 468 ºF. These specifications are slightly lower than the measured values, hence the actual heat recovery should be at or above the values specified in Figure 16. In general, it is reasonable to expect heat recovery in the range of 1.0 to 1.2 MMBtu/hr.

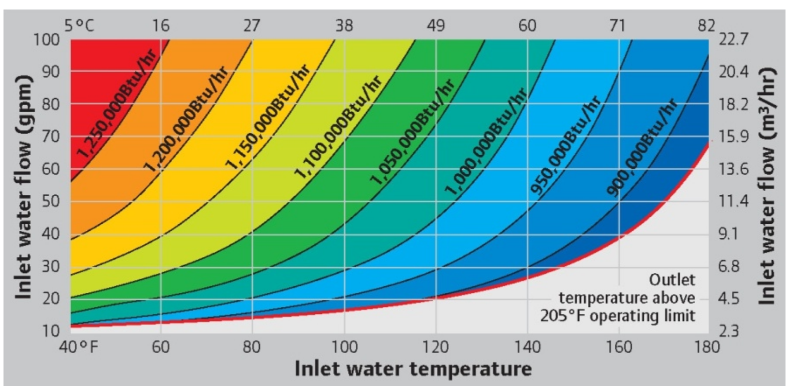

Figure 16. FP250 Heat Recovery Specifications

5.2.2 Emissions: Verify Low Emissions

A full EPA compliance level emissions test was conducted on the FP250 on October 17, 2012. The engine under test was Ener-Core's 'G3' design intended to eliminate 'leak paths' that allow a portion of the aspirated fuel/air mixture to bypass the oxidizer and exit at the turbine exhaust. These 'leak paths' are a normal element of the conventional turbine design that use aspirated air to provide cooling and sealing to internal turbine components. Details of the emissions testing are given in section 4.4.5 above.

In addition to the planned emissions testing at the turbine exhaust, Ener-Core contracted with the testing contractor (Integrity Air) to perform a single, 35-minute sampling run at the oxidizer outlet (turbine inlet). The purpose of the test at the oxidizer outlet was to characterize emissions directly from the oxidizer in order to obtain results independent of any excess emissions due to bypass of the aspirated fuel/air mixture around the oxidizer through the 'leak paths' within the turbine.

Table 8 summarizes the emissions test results and compares emissions from the turbine and oxidizer with the CARB DG 2013 standard [8] and with EPA AP-42 [9] emission factors for best available control technology for LFGE technologies. Note that the AP-42 best listed control device is an enclosed flare for NO_x, and is a boiler/steam turbine for CO and PM.

The success criteria for this performance objective were to meet the CARB 2013 distributed generation standards for NO_x, CO and NMOC and the AP-42 NO_x, CO and PM emissions for the best listed control device.

The FP250 demonstrated extremely low NOx emissions at 3.5% of the CARB 2013 standard and 0.4% of the AP-42 emission factors for the best listed control device (enclosed flare). NMOC emissions from the FP250 turbine exhaust also met the CARB 2013 standard.

The FP250 did *not* meet the success criteria for CO emissions at the turbine exhaust. CO emissions were 357.0% of the CARB 2013 standard and 312.5% of AP-42 emissions for best control device (boiler/steam turbine). However, emissions at the oxidizer outlet *were* lower than the CARB 2013 standards and the best AP-42 emission factor.

The difference in the results at the turbine exhaust and oxidizer outlet is likely due to a small, residual leak path allowing aspirated LFG/air mixture to bypass the oxidizer and appear in the turbine exhaust. The methane in the landfill gas is thought to be partially oxidized to carbon monoxide as it passes over hot surfaces in the engine and recuperator after it is re-introduced into the flow path. The presence of such leak paths was a known design issue from the beginning of the project and Ener-Core engineers worked throughout the demonstration period on means to eliminate these paths. These efforts culminated in the modified 'G3' design that was tested at Ft. Benning. Ener-Core modified the 'G3' engine by separating the primary and secondary flows such that aspirated fuel did not bypass the oxidizer. The design intent was to have zero aspirated air/fuel mixture entering the secondary flow path.

A rough calculation of the leak rate can be made as follows. The CO in the exhaust was 4.5ppm and CH_4 in the exhaust was 5.8 ppm. Assuming all the CO and CH_4 was introduced through a seal leak and that all CH_4 was oxidized to CO, this amounts to 10.3 ppm CH_4 leaking. At 1.5% fuel/air ratio there is 15,000 ppm CH_4 aspirated in the system. This yields a leak rate of 10.3/15,000 = 0.07%. While the leak rate is quite small, it prevents the FP250 'G3' engine design from meeting the tightest CO emissions standards. Ener-Core has addressed this concern by offering a system configuration where the fuel is compressed and injected into the oxidizer instead of aspirated into the turbine's compressor. This solution avoids secondary flow path issue.

Although the FP250 failed to meet the demonstration objectives for CO emissions, the CO emissions at the turbine exhaust were nonetheless considerably lower than uncontrolled emissions for conventional gas turbines or reciprocating engines based on emission factors given in AP42 sections 3.1 for gas turbines and section 3.2 for reciprocating engines. FP250 CO emissions at the turbine exhaust were 5-7% of the emissions for these competing technologies.

Total particulate matter (PM) emissions were measured at the turbine exhaust (but not at the oxidizer outlet). PM emissions exceeded the AP42 emission factor for best control device (boiler/steam turbine). The CARB 2013 standard does not state an emissions limit for PM.

Table 8. Emissions Results and Comparisons

	FP250 (turbine exhaust)	FP250 (oxidizer exhaust)	CARB 2013 (1)	AP42 (3)
Nitrogen Oxides (NOx) - lb/hr	0.0005	0.0016	0.0150	0.1310
Carbon Monoxide - lb/hr	0.0750	0.0120	0.0210	0.0240
Sulfur Dioxide - lb/hr	0.0110	0.0050	na	na
Total PM - lb/hr	0.0360	na	na	0.0101
NMOC as Carbon (lb/hr)	0.0500	0.0071	na	na
NMOC as Hexane (lb/hr) (2)	0.0035	0.0005	0.0042	na
Percentage Comparisons				
	FP250 (Turbine):CARB 2013	**FP250 (Turbine):AP42**	**FP250 (Oxidizer): CARB 2013**	**FP250 (Turbine):FP250 (Oxidizer)**
Nitrogen Oxides (NOx)	3.5%	0.4%	11%	33%
Carbon Monoxide	357.0%	312.5%	57%	625%
Sulfur Dioxide	na	na	na	220%
Total PM	na	357.1%	na	na
NMOC as Carbon	na	na	na	704%
NMOC as Hexane (2)	82.9%	na	12%	704%
Note (1): The CARB 2013 DG standards are expressed in terms of lb/MWhr. Lb/hr values given here are computed based on net FP250 power output during the emissions test, or 210 kW.				
Note (2): The CARB 2013 standard for NMOC emissions is expressed in terms of lb/hr as hexane. According to SCAQMD method 25.3, a factor of 14.36 lb/lbmol Carbon should be used to convert lb/hr as Carbon to lb/hr as hexane. This factor has been applied here to the FP250 measurements to allow comparison with the CARB standard.				
Note (3): The AP42 emission factors are given in terms of pound pollutant per million dscf methane. Results in lb/hr are calculated using 56 scfm pure methane to obtain the 3.4 MMBtu/hr heat input needed to operate the FP250.				

5.2.3 Emissions: NMOC Destruction Efficiency

The success criterion for this objective was to achieve a NMOC destruction efficiency that meets or exceeds the EPA AP-42 destruction efficiency for best control device (boiler/steam turbine) of 98.6%.

NMOC (as Carbon) at turbine exhaust was 0.05 lb/hr. NMOC (as Carbon) at the fuel inlet was 11.6 lb/hr - resulting in a destruction efficiency of 99.6% [12]. The objective was met.

5.2.4 Emissions: Greenhouse Gas Reductions

The demonstration plan success criteria for GHG reductions attributable to the FP250 and the demonstration results are as follows.

- Objective: Greater than 800 metric tons CO2e emissions avoided emissions due to power generation. This objective was met if propane use for LFG augmentation is not considered (1018 to 1153 metric tons CO_2e/yr) and was nearly met (737-767 metric tons CO_2e/yr) when propane usage during the demonstration period is accounted for.

- Objective: Greater than 8000 metric tons gross CO2e emissions reduction due to methane destruction. This objective was met whether or not the increased FP250 destruction efficiency over the flare is taken into account (8461 to 8495 metric tons CO_2e/yr). These results account for the percentage of propane used to supplement the LFG during the demonstration period; however it should be noted that the propane percentage will increase in out years as the LFG generation from the landfill declines.

- Objective: Greater than 10 percent increase in GHG reduction compared to the baseline flare. This objective was met if propane use for LFG augmentation is not considered (12 to 14 percent increase) and was nearly met (9 percent) when the demonstration period propane usage is accounted for.

Table 9 presents summary results for net GHG emissions reductions attributable to the FP250. Details of the calculations, data sources, and assumptions that were used to arrive at the summary results are presented in Appendix D. The results in these tables are annualized over a base year (2012) representing the bulk of FP250 operations during the demonstration. There are a number of considerations to be made for a fair assessment of net annual GHG reductions as described in the following paragraphs. Alternative results are presented in the Tables depending on the operating scenario and assumptions that are made.

The primary GHG emissions reduction for the FP250 demonstration is the result of electric utility emissions offset by the power produced by the FP250, or the avoided emissions that would have resulted from generating the same amount of power on the local (Georgia) utility grid. This amounts to GHG emissions reduction of 1018 metric tons CO_2e/yr.

The FP250 also destroys methane, and this direct emissions reduction is a much larger GHG reduction than the avoided emission reduction at 8495 metric tons CO_2e/yr (assuming 100% methane destruction efficiency for both the FP250 and the Flare). However, methane is also destroyed by the existing (baseline) candlestick flare at the demonstration site, so any incremental reduction would be due to increased methane destruction efficiency of the FP250 over the Flare. This incremental reduction could not be determined directly from demonstration data since the methane destruction efficiency of a candlestick flare cannot be reliably measured. In addition, there is little data available on the destruction efficiency of open candlestick flares. The EPA NSPS requirements for solid waste landfills specify an emissions control device capable of an NMOC destruction efficiency of 98% [13]. A methane/NMOC destruction efficiency of 98% is a common design specification for open flares. For the purpose of estimating the potential magnitude of the incremental increase in GHG reduction, a 98 percent destruction efficiency is assumed for open flares and the measured NMOC destruction efficiency of 99.6% was used for the FP250. The estimated incremental increase in GHG emissions reductions amounts to 136 metric tons CO_2e/yr – for a total emissions reduction of 1153 metric tons CO_2e/yr or about 13% additional reduction compared to the avoided emission alone.

Another potential source of GHG reductions attributable to the FP250 compared to the baseline flare is a reduction in supplementary fuel usage for the existing flare pilot since, at Ft. Benning, the flare was not operated whenever the FP250 was operating. On an annual basis, this amounts to 29.6 metric tons CO_2e/yr.

Table 9. Summary of Total Net Annual CO_2e Emissions due to FP250

Item	Quantity	Units	Notes
Total net annual CO2e emissions reductions due to FP250 (2012): Avoided emissions only.	1018	metric tons CO2e/yr	Avoided emissions due to net power generation only.
Total net annual CO2e emissions reductions due to FP250 (2012): Avoided emissions plus net direct emissions reductions (FP250 - Flare).	1153	metric tons CO2e/yr	Includes avoided emissions due to net power generation plus the difference in direct emissions reductions for methane destruction between the flare (baseline) and the FP250.
Total net annual CO2e emissions reductions due to FP250 (2012). Avoided emissions plus net direct emissions reductions, less FP250 emissions from propane use.	737	metric tons CO2e/yr	Includes avoided emissions due to net power generation plus the difference in direct emissions reductions for methane destruction between the flare (baseline) and the FP250, less the emissions due to propane combustion for startup and LFG augmentation at Ft. Benning.
Total net annual CO2e emissions reductions due to FP250 (2012). Avoided emissions plus net direct emissions reductions, less net (FP250 - Flare) emissions from propane use.	767	metric tons CO2e/yr	Includes avoided emissions due to net power generation plus the difference in direct emissions reductions for methane destruction between the flare (baseline) and the FP250, less the emissions due to propane combustion for startup and LFG augmentation at Ft. Benning and accounting for propane savings for flare pilot.
FP250 additional GHG reduction compared to baseline flare.	12%	%	Assuming methane DRE For FP250 and Flare are equal (100%). FP250 uses all available fuel when operating - no excess to flare.
FP250 additional GHG reduction compared to baseline flare accounting for better FP250 DRE compared to flare.	14%	%	Accounting for improved FP250 DRE compared to Flare. FP250 uses all available fuel when operating - no excess to flare.
FP250 additional GHG reduction compared to baseline flare: accounting for net propane usage.	9%	%	Accounting for improved FP250 DRE compared to Flare less emissions due to net CO2 usage. FP250 uses all available fuel when operating - no excess to flare.

5.2.5 Economic Performance

The demonstration performance objectives for economic performance were to obtain a positive life cycle NPV and a simple payback of less than 5 years. According to the detailed economic assessment presented in section 5.3 below, these objectives were not met at current electricity prices at Ft. Benning.

Positive life cycle NPV is achieved when the electricity price exceeds \$0.10/kWh. A 5-year simple payback is achieved when the electricity price reaches \$0.18/kWh. The current electric price at Ft. Benning is \$0.069/kWh excluding any renewable energy premium.

Ener-Core plans that, as manufacturing steps up and economies of scale are realized, capital and O&M costs will be reduced and future FP250 installations will show positive life cycle NPV at lower electricity prices.

5.2.6 Availability, Reliability and Operability

In order to be successful, the FP250 must provide sufficient availability, reliability and ease of use so that the economic value of power production is realized and no undue burden is placed on operations staff.

Availability is a quantitative metric that is given as the percentage of time that the system is either operating or capable of operation if down for unrelated reasons (such as, in this application, a grid failure or failure of the LFG collection system). Reliability is both a quantitative and qualitative metric that assesses the robustness of the system in terms of likelihood of failure or operational problems, the consequences of such problems, and the ability to recover.

Availability and Reliability were assessed quantitatively in accordance with ANSI Standard 762 [10] which uses a specific categorization of operating and downtime hours. Data were downloaded and reviewed on a weekly basis. Whenever the system shut down, Southern requested an explanation of the cause for the shutdown and Ener-Core would typically respond within one to two business days. Southern logged all downtime and assigned a downtime classification in accordance with ANSI Std. 762 to allow quantitative determination of system availability and reliability. Downtime classifications were as follows.

- Service Hours (SH): In operation or available for operation.
- Reserve Service Hours (RSH): Shut down by choice, but otherwise available for operation.
- Planned Outage Hours (POH): Shutdown planned in advance.
- Forced Outage Hours (FOH): Shutdown through no fault of FP250.
- Maintenance Outage Hours (MOH): Unplanned maintenance outage.
- Period Hours (PH): Total hours for defined evaluation period.

In accordance with ANSI Std. 762, availability is calculated as the sum of service hours (SH) and reserve service hours (RSH) as a percentage of period hours (PH). Since there were zero reserve service hours (RSH), availability is simply service hours (SH) divided by period hours (PH). Reliability is calculated as total period hours (PH) less forced outage hours (FOH) as a percentage of period hours.

Southern began logging downtime on the official commissioning date of September 29, 2011; however, due to particulate breakthrough issues discussed above (see section 4.4.1) significant periods of operation did not begin until March 7, 2012. Ener-Core's primary goal stated when operation resumed in March 2012 was to accumulate operating hours. Thus, the period beginning March 7, 2012 and extending through the end of operation on November 18, 2012 is the most representative period during the demonstration to calculate availability and reliability. These figures are presented in Table 10. The downtime log, in its entirety, is included in this report as Appendix C.

Table 10. FP250 Availability and Reliability: March 7 through November 18, 2012

Classification	Hours	Events	Percentage of Period
Total Period Hours	6144.0		99.7%
Total SH Hours	3527.3	35	57.4%
Total RSH Hours	0.0	0	0.0%
Total POH Hours	388.3	1	6.3%
Total FOH Hours	1133.2	21	18.4%
Total MOH Hours	1075.0	12	17.5%
Reliability			82%
Availability			57%

Total availability was only 57 percent during this period - much lower than the 95 percent goal and the 90-95 percent currently specified by Ener-Core. Availability is low due, in part, to planned outages for filter replacements and the G3 engine replacement and, in part, due to a significant number of forced outages. That said, there were also a significant number of unplanned maintenance events (MOH) that resulted in shutdowns. If the forced and planned outage hours are subtracted from the period hours, the availability increases to 76%.

The reliability logged in the demonstration (82%) comes closer to the goal due to the significant number of forced outages that occurred because of circumstances beyond the control of Ener-Core. Forced outages were primarily caused by unrecoverable grid faults and were also caused by failures of the LFG extraction system. In some cases, a shutdown was initiated by a grid fault, but the system remained down for a longer period than necessitated by the grid fault for troubleshooting or maintenance. Since all of the hours for these events were generally classified as forced outages, Southern feels that the reliability results give the benefit of the doubt to the FP250.

Ease of use is a qualitative metric that is assessed based on operating experience during the demonstration period as documented by narratives and interviews with operators and project participants during and at the conclusion of the project. The ease of use assessment encompasses the entire design and installation process, including permitting and other approval requirements. The acceptability of a newly introduced technology is partly dependent on the subjective experience of operations and maintenance personnel. If these personnel require highly specialized training, or intensive permitting and approval processes, the cost of installation, training, and operations increases. Difficulty with system operation can also reduce availability, since when the system fails it is less likely that someone with the correct expertise will be immediately available.

Due to ongoing engineering development activities during the Ft. Benning demonstration, Ener-Core employed a technician with prior experience working with the MT250 micro-turbine as a full time on-site operator. This technician was on site on a daily basis to monitor FP250 operations, LFG extraction system performance, and conduct system improvement, maintenance and troubleshooting activities as needed. Southern had frequent contact in person and via phone and email with the on-site technician, as well as other Ener-Core engineering and controls staff who were periodically on site for special projects.

During normal operations, the FP250 operated automatically without intervention and Southern witnessed that the FP250 could be monitored and controlled remotely by laptop PC or smartphone. Fault detection and shutdown were fully automated. System startup continued to require operator monitoring and minimal intervention throughout the demonstration period. Ener-Core reports that startup has now been fully automated and that this has been demonstrated on their engineering development test system; however, Southern has not had the opportunity to witness automated startup. Southern's impression is the FP250 has the near-term potential for fully automated, unattended operation; however this was not verified during the demonstration.

5.3 ECONOMIC ASSESSMENT

This section presents a life cycle cost analysis (LCCA) for implementation of the FP250 in a landfill gas to energy application. The analysis is informed by the Ft. Benning demonstration, but has been generalized so that the results are applicable at other suitable sites and with other similar fuel sources (e.g., digester gas). All assumptions and information sources are fully documented to give credibility to the results and to aid in adaptation of the analysis to the reader's unique situation.

The life cycle assessment approach used herein conforms to the requirements and conventions specified in the Life Cycle Costing Manual for the Federal Energy Management Program (FEMP) - also known as 'Handbook 135'. The discount rate used for this analysis (3%) was obtained from the 2012 annual supplement to Handbook 135. The NIST Building Life Cycle Cost (BLCC) software, version 5.3-12 was used to model inputs and calculate the LCCA results for various energy price scenarios.

A number of other resources were also used to guide the life cycle assessment for this demonstration. EPA's Landfill Methane Outreach Program (LMOP) Handbook Chapter 4, Project Economics and Financing [15] provided general guidance on evaluating economics for landfill gas to energy projects and specific cost figures for competing LFGE technologies. EPA's LMOP 'LFG_Cost' model has been used as a guide to identify cost elements and default values particular to landfill gas to energy projects and is also used to estimate costs for comparable LFGE technologies. The Environmental Cost Analysis Methodology (ECAM) Handbook [16] was also consulted as a guide to conducting economic analyses where environmental costs are a factor.

5.3.1 Life Cycle Assessment

The life cycle economic analysis is based on capital and operation/maintenance costs and revenues associated with electricity production during the demonstration period and projected over the expected lifetime of the FP250 equipment. Costs specifically associated with the demonstration program or with product development are excluded as non-typical of a normal installation. The analysis is 'simplified' in the sense that it does not account for costs associated with financing or taxes, or for 'revenues' or cost offsets associated with renewable energy credits, tax credits or other incentives that may be available in some locales for landfill gas to energy or other waste to energy projects.

The LCCA presented here models a 'typical' FP250 installation where (1) there is sufficient LFG (or other waste fuel) to fully operate the FP250 without augmentation, (2) there is a pre-existing LFG collection and extraction system and flare and (3) the flare operates concurrently with the FP250 to consume excess fuel. The LCCA methodology and BLCC model are also used, in a separate case, to evaluate the economics of continued operation of the FP250 at Ft. Benning.

The life cycle economic performance of the FP250 was assessed based on standard economic indicators of financial performance including the net present value (NPV), adjusted internal rate of return (AIRR) and simple and discounted payback periods. These indicators are derived from cash flow analysis accounting for initial capital and installation costs, ongoing operation and maintenance costs, and revenues representing the value of the power produced by the FP250 system over the projected useful life of the system. That analysis accounts for the time value of money at the prescribed discount rate.

According to Ener-Core, in a typical installation and with proper maintenance, the FP250 should provide service for 20 years or longer. This period equates to a lifetime of 160,000 hours at 8,000 operating hours per year. For the purpose of the economic assessment, the LCCA study period was taken as 20 years.

The LCCA was completed in *constant dollars* (excluding inflation) per recommendations for non-financed projects in the BLCC model documentation and Handbook 135. All discount rates and price escalation rates are entered in real terms (without inflation).

Initial investment costs are modeled as 'overnight' costs as of the service date. This practice is consistent with DOE practice for determining levelized costs for renewable energy technologies. The service date is modeled as April 1, 2012 for consistency with DOE energy price escalation rate tables. As discussed above, the actual starting date with the goal of continuous operation was in March 2012.

5.3.2 Energy Costs and Revenues

Electrical energy generated by the FP250 is fed back into the local grid operated by Flint Energy at Ft. Benning and directly offsets power purchases from Georgia Power. For the purpose of the analysis, the value of electric power at Ft. Benning is modeled at $69/MWh ($0.069/kWh). This is the 2013 rate that Ft. Benning charges to reimbursable customers on the base and is based on previous year billings in accordance with applicable regulations [17]. The rate that Ft. Benning pays to Georgia Power varies with time of day and load conditions and includes various fees and facilities and access charges, making it difficult, if not impossible to establish a representative rate based on actual charges.

The Ft. Benning energy manager reported in early 2013 that there is no mechanism in place on the base to account for a premium value on renewable energy (over and above the energy price). The Department of the Army policy for renewable energy credits section 5.f.(1) [18] states that the Deputy Assistant Secretary of the Army for Energy & Sustainability (DASA E&S) is the point of contact for all renewable energy valuation issues. Southern contacted DASA E&S for clarification on renewable energy valuation in renewable energy project life cycle cost assessment. For appropriations funded projects such as the Ft. Benning demonstration, there is no value assigned to renewable energy. Renewable energy valuation is monetized within the LCCA only in cases where RECs are to be sold and the revenue is used to reduce the cost of the project - a situation that may occur in privately financed projects. Army policy states that 100% of RECs associated with appropriations-funded projects will be kept and retired via the Army Energy and Water Reporting System (AEWRS). As such, there is no monetary value that can be applied for this demonstration. However, it is possible that a renewable energy premium might be applicable for a future, privately-financed project within DoD. As such, the value of such a premium is estimated for the LCCA and the economic impact is assessed in section 5.3.4 below.

The BLCC does not explicitly model revenues associated with energy generated from renewable energy projects. Southern contacted the BLCC developers at NIST for clarification and it was confirmed that the preferred approach for modeling revenues from energy generation using the BLCC is to apply a negative energy consumption value.

In addition to electricity, propane is used for startup fuel for the FP250 and is currently also used to supplement the LFG so that sufficient heat input is provided to operate the FP250. Propane is also used as fuel for the flare pilot. There is a savings in flare pilot fuel during FP250 operations at the 1st Division Rd Landfill since, as there is no excess LFG fuel, the flare is shut down during FP250 operation. Propane prices paid by Ft. Benning are based on the Oil Price Information Service (OPIS) daily rate plus delivery on the day of delivery and varied from $1.04 to $2.05/gallon in 2012. US Energy Information Administration (EIA) prices for propane in 2012 averaged $1.19 wholesale and $3.01 retail (per gallon). Since information on the average propane price per gallon paid at Ft. Benning was unavailable, the average of the EIA wholesale and retail prices ($2.10/gallon) was used to model propane energy costs for the LCCA. In a typical application, Southern considers the EIA propane costs to be more representative than prices paid by Ft. Benning.

For continued operations at Ft. Benning, the possibility of installing a natural gas line to provide supplemental fuel to the FP250 has been discussed. The FY13 cost for natural gas charged to reimbursable customers at Ft. Benning is $.621/therm (or $6.21/MMBtu). This is based on 2012 costs. At $2.10/gallon, the normalized cost of propane is $22.92/MMBtu, or about 3.7 times the cost of natural gas. However, a natural gas pipeline would need to be extended for a distance of over one mile to provide the gas to the FP250 and minor modifications to the fuel delivery system would be required to allow the natural gas to be used.

5.3.3 LCCA Inputs and Assumptions: Typical Case

As discussed above (section 3.1) LFG recovery at the 1st Division Road Landfill was lower than expected and proved insufficient to operate the FP250, necessitating the use of supplemental fuel to complete the demonstration. This situation is atypical in that site selection activities would normally be expected to verify that sufficient fuel was available before a system was installed. The typical case modeled here assumes that there is sufficient LFG (or other nominally zero-cost ‘waste’ fuel) to fully operate the FP250 without augmentation, there is a pre-existing extraction system and flare and the flare operates concurrently with the FP250 to consume excess fuel.

Southern recognizes that, in many cases, potentially suitable landfills may not already be equipped with an extraction system; however, this lack would have to be addressed for the implementation of any LFGE technology and the extra costs are not representative of the performance or economics of the FP250 per se. For non-LFG fuel sources such as digester gas, extraction system costs are not relevant. Thus, Southern considers that the assumptions made here for the typical case provide broad, general comparability with other LFGE technologies and other non-landfill applications for the FP250. A discussion of LFG extraction system costs is provided in section 5.3.6 below.

Table 11 (below) presents BLCC inputs for each LCCA cost element that was modeled for the typical case. Notes are provided to document data sources and any special considerations for each model input.

FP250 availability for the typical case was modeled at 91.3%. This value was selected for consistency with Ener-Core’s schedule for non-annual maintenance/overhaul of system components which presumes 80,000 hours of operation over 10 years – or 91.3% availability on average. According to Ener-Core, actual availability in typical service is expected to range from 90 to 95 percent.

Residual value after the 20 year study period was modeled as zero based on Handbook 135 guidance which recommends straight line pro-ration of capital costs over the system lifetime. Since, in this case, the system lifetime coincides with the study period, straight line proration gives zero residual value. Any residual value remaining after the system has exceeded its lifetime is presumed to be offset by decommissioning and disposal costs.

In the BLCC, non-annually recurring maintenance/overhaul or component replacement costs may be modeled as capital replacement costs or non-annual OM&R costs. The distinction is that capital replacements are funded from capital accounts whereas non-annual OM&R costs are funded from operating accounts. The distinction may have tax implications, but is unimportant within the context of this analysis.

The FP250 has significant non-annual overhaul/replacement costs occurring at various time intervals throughout the system lifetime. Over the system lifetime, the cumulative present value cost of these overhauls/replacements approaches the initial capital cost. Table 12 gives the schedule and costs for each of these elements (including parts, materials and labor). Labor costs are modeled at $50/hour based on US bureau of labor statistics average hourly labor rates for industrial mechanics (approximately $20/hr) multiplied by a cost of doing business factor of 2.5. Details of *annual* OM&R costs are given in Table 13.

The capital investment cost modeled in the typical case represents the average of high and low range estimates provided by Ener-Core for base equipment and site specific equipment design, construction, and commissioning costs. The capital cost breakout including high and low range estimates is provided in Table 14.

Table 11. LCCA Cost Elements for the FP250: Typical Case

LCCA Element	Value	Units	Data Sources and Notes
End of Year Discounting	yes	na	Per non-MILCON project.
Constant Dollar Analysis	yes	na	Per non-financed project. Discount rate exclusive of inflation.
Discount Rate	3%	%	Per OMB Circular A94 2012 and 2012 annual supplement to Handbook 135.
Base Date	4/1/2012	date	Consistent with starting date for DOE energy price escalation rates used in the BLCC.
Service Date	4/1/2012	date	Service date modeled to coincide with base date.
Study Period	20	years	Based on expected service life of FP250.
Energy Production: electricity	-1,759,534	kWh/yr	Negative value used to reflect energy production vs. usage. Based on demonstration data for G3 engine average net output (220 kW), annualized at 91.3% availability. Location: Georgia.
Energy Cost: electricity	$0.069	$/kWh	Ft. Benning rate charged to reimbursable customers (based on 2012 costs). Price escalation rates per BLCC/DOE. No annual demand charges or rebates.
Energy Usage: propane	230	gallons/yr	Average value from demo data. For startup only. Assumes two maintenance shut downs per year (best case). Assumes total gallons used per startup for (future) single burner, 20 hour startup program is the same as for current 2 burner 4-6 hour startup sequence.
Energy Cost: propane	$2.10	$/gallon	Average of 2012 EIA wholesale and retail rates for Georgia. Price escalation rates per BLCC/DOE.
Capital Component: FP250, Investment Cost	$1,254,313	$	Mid-range cost. Includes: FP250, BoP, site prep and installation. 'Overnight' cost. No cost phasing.

LCCA Element	Value	Units	Data Sources and Notes
Capital Component: FP250, Investment Cost, Residual Value	0	%	Straight line proration over study period (same as system lifetime) per FEMP 135 manual.
Capital Component: FP250, Replacement Cost	$0	$	Capital replacements are assumed to be funded from capital accounts rather than current accounts. This may have tax implications. For this analysis, replacements are presumed to be funded from operating accounts rather than from capital accounts and are entered as Non-Annually Recurring OM&R Costs.
Annual OM&R	$47,400	$	Operation ($16k) and Maintenance (balance). Including filter cleanings. Materials and labor.
FP250, Non-annual OM&R Cost, 1.5 yr	$22,900	$	Filter replacement.: 13 occurrences in 20 yr study period.
FP250, Non-annual OM&R Cost, 2.5 yr	$2,200	$	Replace igniter: 7 occurrences in 20 yr study period
FP250, Non-annual OM&R Cost, 5 yr	$85,725	$	Engine overhaul and replace warmer/combustor: 3 occurrences in 20 yr study period (years 6,11,and 16)
FP250, Non-annual OM&R Cost, 10 yr	$207,500	$	Replace recuperator, oxidizer internals and media, transition tee and expansion joint (bellows): 1 occurrence in 20 year study period (year 11)
FP250, Non-annual OM&R Cost, 15 yr	$54,000	$	Replace/overhaul generator and gearbox. Year 16. Residual value of this replacement at year 20 is neglected.

Table 12. Non-annual OM&R Cost Detail

Non-annual replacement/overhaul Item	Parts Cost	Labor Hours	Total Cost ($50/hr labor)	Interval
Replace Oxidizer/Turbine Filter	$22,500	8	$22,900	1.5 yr/12,000 hours
Replace Combustor/Warmer Igniter	$1,800	8	$2,200	2.5 yr/20,000 hours
Engine Overhaul	$70,000	170	$78,500	5 yr/40,000 hours
Replace Warmer Combustor	$6,825	8	$7,225	5 yr/40,000 hours
Subtotal for 5 year interval OM&R	***$76,825***	***178***	***$85,725***	***5 yr/40,000 hours***
Recuperator Replacement (labor included with engine overhaul at same time)	$80,000	-	$80,000	10 yr/80,000 hours
Replace oxidizer internals and media	$82,500	96	$87,300	10 yr/80,000 hours
Replace Transition Tee and Expansion Joint (Bellows)	$33,000	144	$40,200	10 yr/80,000 hours
Subtotal for 10 year interval OM&R	***$195,500***	***240***	***$207,500***	***10 yr/80,000 hours***
Overhaul Generator and Gearbox	$44,000	200	$54,000	15 yr/120,000 hours

Table 13. Annual OM&R Cost Detail

Maintenance Item	Q1	Q2	Q3	Q4	Totals
Engine Borescope Inspection		$ 3,300		$ 3,300	$ 6,600
Filter Cleaning		$ 4,600		$ 4,600	$ 9,200
EX250 Yearly Maintenance				$ 6,600	$ 6,600
Recuperator Cleaning		$ 4,500		$ 4,500	$ 9,000
Weekly Inspection	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 16,000
Subtotal	**$ 4,000**	**$ 16,400**	**$ 4,000**	**$ 23,000**	**$ 47,400**

Table 14. FP250 Capital Cost Breakout

Item	Typical Amount (low range)	Typical Amount (high range)	Typical Amount (Average)	Notes
Capital equipment costs (base)	$895,000	$895,000	$895,000	Current (2013) List price. Includes operator training costs.
Site specific engineering/design costs	$22,375	$35,800	$29,088	2.5-4% of list price. Includes permitting cost.
Management costs (for design/construction/ commissioning)	$17,900	$26,850	$22,375	2-3% of list price
Site specific capital costs	$134,250	$196,900	$165,575	Combined costs for electrical interconnect (10-15% of list price) and fuel delivery equipment (5-7% of list price). Fuel delivery system includes LFG and startup fuel systems.
Shipping	$13,425	$22,375	$17,900	1.5-2.5% of list price.
Site preparation/equipment installation	$89,500	$134,250	$111,875	10-15% of list price
Commissioning	$10,000	$15,000	$12,500	$40-60 per kW
Total	$1,182,450	$1,326,175	$1,254,313	Average value used for reported results.

5.3.4 LCCA Results: Typical Case

Based on the model inputs presented in detail above, the FP250 BLCC results begin to show a positive return on investment once the price of electricity reaches $0.10/kWh. As noted above, Ener-Core expects equipment costs to decrease once manufacturing steps up and economies of scale are realized. In addition, current O&M cost estimates are conservative pending further operating experience that will allow Ener-Core to optimize maintenance and parts replacement schedules, and reduce the cost of replacement parts. Lower capital and O&M costs would provide a return on investment at a lower electricity price.

Table 15 summarizes LCCA results from BLCC output for electricity prices ranging from $0.069 to $0.15 per kWh. In all cases, the total present value OM&R costs (annual and non-annual) over the 20 year study period is $1,319,978 and the total 'overnight' capital investment cost is $1,254,313.

For the Ft. Benning case, at $0.069/kWh, the life cycle NPV (net savings) is negative and payback is not reached during the study period. A 7-year simple payback is not achieved until the electricity price reaches $0.15/kWh.

The current Ft. Benning electric price is consistent with the EIA December 2012 US average industrial sector price ($0.0654/kWh), and somewhat higher than the industrial sector price in Georgia ($0.0565/kWh) [19]. Commercial sector electric prices (as of December 2012) are closer to the $0.10/kWh break-even price at $0.0982/kWh nationwide and $0.0923/kWh in Georgia. Electricity prices are currently trending downward in Georgia due to decreasing natural gas prices. That said, the Ft. Benning energy manager reports that Plant Vogtle nuclear units 3 and 4 will cause a rate increase in early 2016 and again early in 2017.

Under its Green Energy Program, Georgia Power sells renewable energy at a premium of $35/MWh ($0.035/kWh) for standard green energy and $50/MWh for premium green energy (comprised of at least 50% solar). Georgia Power supports distributed generation and maintains a program to purchase renewable and non-renewable energy at their avoided energy cost. In 2012, Georgia Power's avoided energy costs were $123.26/MWh (peak) $75.12/MWh (peak season/off peak hours) or $74.16 (off peak) [20].

Although, at present, no monetary premium is recognized by the Army or the marketplace, a valuation of $35/MWh above Ft. Benning's nominal current energy price ($69/MWh) yielding an energy price of $0.104/kWh would produce a positive life cycle net savings of $154,016 for the FP250 under the typical case model. In this instance, the SIR would be 1.12, the AIRR would be 3.60%, simple payback would occur in year 14 and discounted payback would occur in year 18.

Table 15. Typical Case BLCC LCAA Results at Varying Electricity Prices

Electricity Price ($/kWh)	PV of Energy Savings ($)	PV of non-investment savings	Net Savings PV	Simple Payback (yr)	Discounted Payback (yr)	SIR	AIRR (%)
$0.069	$1,807,413	$487,435	($766,878)	not reached	not reached	0.39	-1.76%
$0.08	$2,096,837	$776,859	($477,454)	not reached	not reached	0.62	0.56%
$0.09	$2,359,950	$1,039,972	($214,341)	19	not reached	0.83	2.04%
$0.10	$2,623,063	$1,303,084	$48,771	15	20	1.04	3.20%
$0.11	$2,886,175	$1,566,197	$311,884	13	15	1.25	4.15%
$0.12	$3,149,288	$1,829,310	$574,997	9	13	1.46	4.96%
$0.13	$3,412,401	$2,092,423	$838,110	9	12	1.67	5.67%
$0.14	$3,675,514	$2,355,535	$1,101,222	8	9	1.88	6.30%
$0.15	$3,938,626	$2,618,648	$1,364,335	7	8	2.09	6.86%
$0.16	$4,201,739	$2,881,761	$1,627,448	6	7	2.30	7.37%
$0.17	$4,464,852	$3,144,873	$1,890,560	6	7	2.51	7.84%
$0.18	$4,727,964	$3,407,986	$2,153,673	5	6	2.72	8.28%

5.3.5 Economic Assessment for Continued FP250 Operation at Ft. Benning

The economic assessment for Ft. Benning differs from the typical case primarily because the 1st Division Rd Landfill does not produce sufficient LFG to allow the FP250 to operate (section 3.1.1), requiring the use of supplemental fuel. The amount of supplemental fuel required is expected to increase as LFG production continues to decline in future years. This is a significant cost that weighs against the revenue associated with electricity generation using waste gas. The FP250 is currently using propane for supplemental fuel, but this is relatively expensive and it has been suggested that providing a natural gas supply may be a more economical alternative in the long run.

Another consideration unique to the Ft. Benning installation is that, because all of the available LFG is consumed by the FP250, the flare is not operated when the FP250 is running, so there is a saving of propane fuel for the flare pilot during FP250 operation. This savings was estimated based on flare pilot fuel usage specifications provided by the flare manufacturer (FlareGas Corporation). According to FlareGas, the flare pilot requires 50,000 Btu/hr heat input from the propane fuel. This equates to 4,304 gallons of propane saved per year with the FP250 operating at 91.3% availability as modeled for the typical case.

In addition, as discussed above (section 7.3), Ener-Core has recommended overhaul of the engine, and upgrades to the filter and switchgear before continuing operation at Ft. Benning. The total cost of these upgrades is $242,863. This total breaks down as follows:

- $136,863 for engine overhaul
- $30,425 for filter replacement and upgrade
- $75,575 for switchgear upgrades

To provide natural gas to the FP250, the existing natural gas piping on the base would have to be extended for a distance of somewhat over a mile. According to Interstate Natural Gas Association of America (INGAA) projections for natural gas pipeline infrastructure, 2012 natural gas pipeline costs are estimated at $60k per inch-mile [21]. Southern estimates that a minimum of two inch piping would be required to extend sufficient natural gas service to the 1st Division Road Landfill. Thus, a cost of $120k for the pipeline extension is used to model the economics for this option. In addition, Ener-Core has quoted $26,763 to modify the FP250 fuel supply system to accept natural gas for augmentation – for a total additional cost of $146,763 to implement the natural gas supplementary fuel option.

All other LCCA model inputs and assumptions for the Ft. Benning cases are the same as for the typical case (see Table 11).

Southern performed LCC analysis for two cases specific to the 1st Division Road Landfill installation. Case 1 is to continue use of propane for fuel augmentation and startup. Case 2 is to convert to natural gas for augmentation, but leave the existing propane system in a place for startup. It is possible to also convert the startup system to natural gas, but the estimated cost for the required gas compressor and warmer/combustor modifications is high ($100-150k) and, for the typical case, only two startups per year are planned for routine maintenance activities - so the propane usage/cost for startup would be minimal. Therefore, the natural gas startup option is not considered economical from the outset and was not modeled.

In both cases, the value of the existing equipment on site is considered to be a sunk cost and is not included in the analysis. Thus, this analysis applies specifically to the economics of continued operation of the system at Ft. Benning.

In Case 1 (propane augmentation), the total cost of the recommended system updates ($242,863) is modeled as the initial investment. In Case 2 (natural gas augmentation), the cost of the updates and the cost of the natural gas pipeline and associated system modifications ($146,763), or a total of $390,626 is modeled as the initial investment.

A reasonably reliable estimate of the rate at which LFG recovery at the 1st Division Road Landfill is expected to decline in future years was given in the modeling results provided by SCS engineers (section 3.1.1). Based on this, the required amount of supplemental fuel can be estimated in future years. Table 16 gives the supplemental fuel requirements for propane and natural gas for each of the 20 LCCA years. This is based on the mid-level projections of LFG recovery in the SCS model and a required heat input for FP250 operation of 3.4 MMBtu/hr.

The BLCC model provides for changes in energy usage in future years using a usage index factor for each subsequent year that applies to base year energy usage in future years. The BLCC usage indices applied in the model are listed in Table 16. The mid-level LFG recovery projections for 2011 closely matched actual landfill performance measured as part of the demonstration in 2012. Therefore, the 2011 estimates are used for LCCA year 1 (base year).

Table 16: Estimates of Required Supplemental Fuel in Future LCCA Years

LCCA year	Estimated LFG Recovery (MMBtu/hr)	Required Supplemental Fuel (MMBtu/hr)	Required Supplemental Fuel (LPG gpy)	Required Supplemental Fuel (NG therm/yr)	BLCC Usage Index
1	3.0	0.4	35,224	31,883	100%
2	2.8	0.6	52,916	47,896	150%
3	2.6	0.8	69,412	62,827	197%
4	2.4	1.0	84,781	76,739	241%
5	2.3	1.1	99,124	89,721	281%
6	2.1	1.3	112,490	101,819	319%
7	2.0	1.4	124,959	113,106	355%
8	1.8	1.6	136,581	123,625	388%
9	1.7	1.7	147,416	133,432	419%
10	1.6	1.8	157,522	142,580	447%
11	1.5	1.9	166,941	151,105	474%
12	1.4	2.0	175,723	159,053	499%
13	1.3	2.1	183,916	166,469	522%
14	1.2	2.2	191,551	173,380	544%
15	1.1	2.3	198,667	179,821	564%
16	1.0	2.4	205,305	185,830	583%
17	1.0	2.4	211,495	191,432	600%
18	0.9	2.5	217,266	196,656	617%
19	0.9	2.6	222,648	201,528	632%
20	0.8	2.6	227,672	206,075	646%

Case 1: Propane Augmentation

BLCC results for this case do not show a positive return on investment until the electricity price reaches $0.25/kWh, so continued use of propane for augmentation is not economical at electricity prices near current levels. In terms of operating cash flow only (neglecting the initial cost of the updates), continued operations at the current electricity price ($0.069/kWh) become uneconomical (negative net cash flow) after the first year of operation.

Apart from the economics, propane usage for augmentation becomes somewhat impractical within a few years simply due to the frequency of tank refills that would be required. In year two, propane usage is estimated to exceed 1000 gallons per week. In year five, propane usage reaches 2000 gallons per week. There are currently two 1000 gallon propane tanks for augmentation fuel at Ft. Benning, so more than one fuel delivery per week would be required beginning in year four or five.

Propane usage for augmentation is not economical compared to natural gas. At the energy prices modeled for the typical case ($2.10/gallon for propane and $0.621/therm for natural gas), the propane cost is about $22.92/MMBtu heat input compared to about $6.21/MMBtu for natural gas.

Case 2: Natural Gas Augmentation

For Case 2, positive life cycle net savings does not occur until the electricity price reaches $0.11/kWh. At this electric rate, simple and discounted payback of the investment in system updates and the natural gas supply occurs in year four. As stated above, in this analysis, the investment cost is the cost of the recommended system updates plus the natural gas pipeline at a total of $389,626. The total present value life cycle OM&R cost is the same as for the typical case at $1,319,978.

In terms of operating cash flow only, continued operations at the current electricity price become uneconomical (negative net annual cash flow) after year five. Cumulative operating cash flow becomes negative after year 10.

With the decreasing LFG availability over time, it will no longer make economic sense on a break-even basis for Ft. Benning to continue operating the FP250 at some point 5-10 years in the future (depending on whether annual or cumulative cash flow is the deciding factor) - even if the initial investment cost of the upgrades is neglected. At current electric rates, cumulative cash flow never amounts to enough to cover the cost of the upgrades. If the upgrade costs are considered, it would not make sense in economic terms alone to continue operating the FP250 at Ft. Benning.

Table 17 shows BLCC output for the operating cash flow. The column for the value of energy consumption represents the value of the electricity produced by the FP250 less the value of the supplementary fuel (natural gas) and the value of propane used for startup as offset by the savings in flare pilot fuel (propane).

Table 17. BLCC Results for Operating Cash Flow, Ft. Benning Case 2: Natural Gas Augmentation (Electricity Price at $0.069/kWh).

LCCA Year	Recurring OM&R	Non-Recurring OM&R	Net Energy Production or Consumption	Total	Cumulative
1	($47,400)	$0	$110,311	$62,911	$62,911
2	($47,400)	($22,900)	$101,783	$31,483	$94,394
3	($47,400)	($2,200)	$93,804	$44,204	$138,598
4	($47,400)	($22,900)	$85,209	$14,909	$153,507
5	($47,400)	($22,900)	$76,482	$6,182	$159,689
6	($47,400)	($87,925)	$68,250	($67,075)	$92,614
7	($47,400)	($22,900)	$59,363	($10,937)	$81,677
8	($47,400)	($25,100)	$51,500	($21,000)	$60,677
9	($47,400)	$0	$43,834	($3,566)	$57,111
10	($47,400)	($22,900)	$35,952	($34,348)	$22,763
11	($47,400)	($318,325)	$28,722	($337,003)	($314,240)
12	($47,400)	$0	$22,121	($25,279)	($339,519)
13	($47,400)	($25,100)	$15,079	($57,421)	($396,940)
14	($47,400)	($22,900)	$8,280	($62,020)	($458,960)
15	($47,400)	$0	$2,130	($45,270)	($504,230)
16	($47,400)	($164,825)	($3,800)	($216,025)	($720,255)
17	($47,400)	($22,900)	($9,575)	($79,875)	($800,130)
18	($47,400)	($2,200)	($15,311)	($64,911)	($865,041)
19	($47,400)	($22,900)	($20,155)	($90,455)	($955,496)
20	($47,400)	($22,900)	($25,180)	($95,480)	($1,050,976)

5.3.6 LFG Extraction System Costs

In the analyses above, it was assumed that a landfill gas extraction system and flare are already in place at the selected site. In Southern's 2010 survey of 471 DoD landfills [3], only 6 landfills were positively identified as having a collection system in place. That said, for the majority of landfills in the database, this information was not available.

There are 10 landfills in the database that have listed waste in place volumes greater than 2.5 million cubic meters and that therefore may be subject to EPA NSPS regulations (for new landfills) or EG guidelines (for older landfills) requiring emissions controls including an LFG collection system and flare. None of these landfills were identified in the database as having a collection system in place - though in all but one case, this information was unavailable. Waste in place volume was not available for 153 landfills, so it is possible that there may be additional DoD landfills subject to NSPS or EG regulations (if applicable).

Based on the discussion above, it would appear likely that many potential sites will *not* have an LFG extraction system already in place.

According to EPA's LMOP LFGE cost model [22], a mid-sized (40 acre) LFG extraction and flare system will cost, on average about $24k per acre, with annual O&M costs of about $4,100 per acre. These values are consistent with extraction system costs estimated for 5 DoD landfills in a recent USACE report [23]. In the USACE report, extraction system costs averaged about $25,600 per acre ranging from $20k to $32k per acre.

If the typical case LCCA model is run with the LMOP capital and O&M costs for an extraction system included, life cycle net savings are not achieved until the electricity rate reaches $0.20/kWh.

5.3.7 Levelized Cost of Energy Comparison

The levelized cost of energy (LCOE) for an energy generating technology is the energy price at which the NPV of the life cycle cost of the technology over the equipment lifetime is zero. The energy price must reach the LCOE value for the project to break even and exceed the LCOE value for the technology application to produce a positive net savings or return on investment. The LCOE thus provides a common basis for comparing the cost of competing energy technologies and assessing the cost competiveness of a given technology.

According to DOE's NREL Open Energy Info database [24], the 2011 median levelized cost of energy (LCOE) for distributed generation technologies is $0.14/kWh. LCOE values in the OpenEI database range from $0.05/kWh to $0.48/kWh with an inter-quartile range of $0.08 to $0.35 per kWh. This is based on 17 cases in the database. NREL's 2012 projected average LCOE value for distributed generation is $0.09/kWh.

EPA's LMOP Project Development Handbook [15] gives typical costs for a micro-turbine (<1MW) in landfill gas applications of $5500/kW capital and $380/kW O&M annually. Using the NREL's online simple LCOE calculator [25], the LCOE for the typical micro-turbine is $0.094/kWh. For a small (<1MW) internal combustion engine in landfill gas application the LMOP handbook gives capital costs of $2300/kW with annual O&M costs of $210/kW. The NREL simple LCOE for the small IC engine is $0.045/kWh. A capacity factor of 91.3%, discount rate of 3.0% and lifetime of 20 years was used in each of these cases for comparability with the FP250 economic analysis.

For the FP250 typical case LCCA modeling inputs ($5700/kW capital cost, $215/kW annual (fixed) O&M and $0.0236/kWh variable OM&R), the NREL simple LCOE for the FP250 is $0.098/kWh.

Based on this limited analysis, the levelized cost of the FP250 per kilowatt-hour appears to be on par with competing distributed generation and LFGE technologies.

6.0 IMPLEMENTATION ISSUES

Section 3.2.2 above provides a comprehensive list of site criteria for FP250 installation. This section highlights and provides additional detail on specific implementation issues encountered during the demonstration.

One of the lessons learned in this demonstration is that a landfill that, based on all readily available evidence, appears to be producing more than enough gas to operate the FP250 may not be producing nearly as much gas as expected. For the 1st Division Rd site, methane flow data available from routine monthly readings at each well head yielded misleading information when aggregated to total well field production (see section 3.1.1). The total landfill area was mistakenly recorded in site records as 48 acres while the actual active area was discovered to be 26.5 acres. The landfill had a history of problems with offsite methane migration suggesting that high levels of gas were being produced. In 2003, modeling based on vent performance tests predicted the landfill would produce 700 cfm LFG with 40 to 50 percent methane content (17-21 MMBtu/hr).

Even with all of this evidence indicating a more than sufficient fuel supply at the 1st Division Road Landfill, it would have been prudent to obtain accurate measurements of methane flow actually delivered to the flare during site selection activities. It is strongly recommended that a representative set of such measurements be obtained for future candidate sites, notwithstanding any other data that may be available.

In the case where an extraction system is not already in place, a thorough study should be conducted to verify sufficient gas is present and may be recovered. This would include a detailed examination of the landfill characteristics including information on the landfill structure and the rate and type of waste acceptance, surface testing to verify gas production and permeation, and, based on these data, careful modeling of the expected LFG recovery rate over time.

Installation managers should understand that the FP250, like other turbine-based technologies, requires a steady fuel supply with a minimum total energy content of about 3.4 MMBtu/hr. That is, the FP250 is only capable of operating near 100 percent of rated capacity and has little turn-down capability. In addition, the FP250 does not tolerate excessive thermal cycling. Continuous 24/7 operation is recommended and the number of restarts over the system lifetime should be minimized to avoid excessive maintenance. It is therefore critical that a sufficient, continuous fuel supply be carefully verified during site selection.

As discussed above (section 5.3.6), it is at least somewhat likely that a potential landfill site under consideration for FP250 application will not have an existing LFG extraction system and flare. In such cases, the cost of the required extraction system may make the project economics less attractive.

Southern has found that the presence of a strong and effective advocate on-base who is able to enroll support from other on-site stakeholders is a key success factor for energy projects.

The FP250 is a newly commercialized technology that is still undergoing minor modifications to improve reliability and operability. These modifications include:

- prevention of turbine wear due to particulate breakthrough (discussed in section 6.1 below),
- a new startup protocol utilizing the warmer only (the combustor will be removed from the system),
- full automation of system startup,
- the capability to continue operation in 'island mode' to prevent unnecessary shut downs due to transient grid faults (applicable to sites where there are frequent grid interruptions)

The performance of these proposed modifications has not been verified as part of this demonstration.

Ener-Core has provided a summary operations and maintenance manual and is in the process of developing full operations and maintenance protocols and procedures and complete system documentation. Southern has reviewed and commented on the summary manual, but has not had the opportunity to review complete system documentation as part of this demonstration.

As the FP250 is a low emissions technology based on proven gas turbine technology, Southern anticipates that regulatory or permitting barriers for future installations will be low. Southern's experience with the Ft. Benning demonstration was that there were no significant regulatory or permitting barriers.

6.1 Filtration between the Oxidizer and Turbine

Particulate matter may be introduced into the FP250 by oxidation of siloxanes present in the LFG, by breakdown of the heat transfer media or internal insulation within the gradual oxidizer, or as a consequence of corrosion of metallic components such as the combustor and warmer.

In order to prevent particulate matter from damaging the turbine wheel or fouling the recuperator, the FP250 design incorporates a filter between the gradual oxidizer and the turbine. The original design employed a 150 micron filter.

After operating less than 400 hours, the original engine was found to have excessive wear on the nozzle and turbine rotor. A root cause analysis was conducted and concluded that the turbine wear was due to media from the gradual oxidizer entering the turbine section of the engine and eroding the nozzle and turbine rotor [7]. Based on this, Ener-Core initiated an effort to improve filtration between the oxidizer and the turbine. Interim filter solutions were installed in order to be able to continue operations while a final solution was developed.

Ener-Core engineered and tested several filter solutions throughout 2012. The first was a 75 micron filter installed in February 2012. After initial testing, this filter was replaced with a 50 micron filter with additional open area in early March 2012. The 50 micron filter performed well over more than 1800 hours of operation. When the G3 engine design was installed in July 2012, the 50 micron filter was replaced with a 40 micron filter. The 40 micron filter performed well over nearly 900 hours of operation until it was replaced as planned in mid-September 2012 with a 5 micron pleated ceramic filter that was intended to be the final filter solution. This required minor piping modifications.

Excessive insulation wear was observed after about 290 hours of operation with the 5 micron filter, leading to filter erosion and particulate breakthrough, which allowed debris to enter the turbine. In order to continue operation, a 75micron filter that was on hand was installed.

Ener-Core has determined that adding a liner in the hot piping upstream of the 5 micron filter will prevent insulation wear and filter erosion and has recommended that this be completed before resuming operations following the system handover. The performance of this solution will not be verified as part of the demonstration.

Ener-Core recommends cleaning the filter after 4,000 hours operation and replacing the filter at 12,000 hours operation. The pressure drop across the filter is continuously monitored, and the filter need not be replaced so long as the pressure drop remains in specification. This maintenance interval can vary based on the system operation and application fuel. For future installations, Ener-Core has adopted special oxidizer media handling procedures to minimize debris generation during assembly.

7.0 TECHNOLOGY TRANSFER

7.1 Commercialization and Implementation

After deployment of FP250 development and field test units in 2011-2012, Ener-Core currently anticipates shipment of the first commercial FP250 systems starting in late 2013. To date, Ener-Core has received one order with shipment targeted for November 2013. The system will be installed at a landfill site in the Netherlands. Ener-Core is currently working to lower the costs and improve the reliability of its commercial products, and expects to lower its costs and prices by approximately 20% in 2014, when it plans to reach its first year target production levels of 15 units per year.

Ener-Core believes that its technology and related systems can tap into several large available gas markets worldwide, including landfill and biogas, coal mines, associated petroleum gas, and mainstream power generation markets. Ener-Core is hopeful that the Ft. Benning project will lead to additional installations within the Department of Defense.

7.2 Publicity, Outreach and Training Activities

Throughout the demonstration, Southern and Ener-Core have engaged in publicity and outreach activities intended to inform the DoD energy community, as well as the broader renewable energy community about opportunities and applications for the FP250 system.

Southern has made presentations on the Ft. Benning demonstration at annual SERDP/ESTCP symposia each year since 2008 as well as at the 2012 Energy, Utility and Environment (EUEC) conference and the 2012 National Defense Industry Association (NDIA) Environment, Energy Security & Sustainability (E2S2) symposium. Southern had an abstract accepted for the 2013 E2S2 symposium, but the conference was cancelled due to federal budget sequestration. Southern plans to present at the 2013 Renewable Energy Technology (RETECH) conference in Washington. Southern has also prepared and distributed project fact sheets through Southern's web site and as conference handouts.

Ener-Core exhibited at the 2011 ARPA-E Energy Innovation Summit as well as sponsoring a ribbon cutting ceremony and reception at Ft. Benning that was attended by high ranking DoD personnel and leaders in the environmental community.

Southern has issued press releases at key project milestones that were widely distributed. Each press release was targeted according to the audience that it would interest. Southern's PR department uses both PRNewswire and BusinessWire to distribute news releases. With each of those services, Southern targets publications that are written for and subscribed to by various preferred audiences (like DoD, defense contractors, energy technology firms), and also targets newsletters and blogs that cover the specific subject matter in the release. For the Ft. Benning demonstration, Southern also targeted the green/renewable energy outlets, DoE-oriented outlets, and energy/power industry publications and web outlets. If Southern has working relationships with other press in the subject area, or a specific publication of interest, Southern will contact and work with those publications directly through phone and email. A large number of news stories and articles were generated through these efforts.

Southern's outreach efforts have been picked up by others that have helped spread the word and educate the DoD energy community. Southern has observed that Dorothy Robyn, former Deputy Undersecretary of Defense – Installations & Environment, has included the Ener-Core project in several presentations at conferences. Southern's landfill database – an early deliverable in this project, has been cited by others in the DoD energy community and referenced as part of the USACE's assessment of LFGE opportunities across DoD.

This report, in its entirety, is intended to provide sufficient guidance for installation managers to decide whether the FP250 is a suitable technology for their applications and to assist them in initiating a thorough planning process to ensure a successful installation.

Table 18 lists outreach activities and resulting news stories known to have resulted from outreach activities conducted as part of this demonstration.

Table 18. Outreach and Education Activities

Date	Type	Venue/Distribution
2008	ESTCP Symposium	Poster presentation
2009	ESTCP Symposium	Poster presentation
2010	ESTCP Symposium	Poster presentation
2011	ESTCP Symposium	Poster and presentation in renewable energy panel
2011	Exhibition/Showcase	ARPA-E Energy Innovation Summit
2011	Feature Initiative	ESTCP Web Site
2011	News Story	13 WMAZ-TV, Columbus GA
2012	EUEC Conference	Presentation in renewable energy session
2012	NDIA E2S2 Conference	Presentation in renewable energy session
Nov-2008	DoD landfill database report	Various DoD requestors
Feb-2011	News Story	Inhabitat.com
Feb-2011	News Story	http://cleantechnica.com
Feb-2011	News Story	http://www.pennenergy.com
Feb-2011	News Story	http://www.smartplanet.com
Feb-2011	News Story	http://www.earthtechling.com
Feb-2011	News Story	http://www.redorbit.com
Mar-2011	News Story	IMT Green & Clean Journal
Apr-2011	News Story	http://www.army.mil
Sep-2011	News Story	Waste and Recycling News
Sep-2011	News Story	United Press International
Sep-2011	News Story	http://www.waste-management-world.com
Sep-2011	Press Release	Various
Nov-2011	News Story	Columbus Ledger-Enquirer
Nov-2011	News Story	WTVM9 News
Nov-2011	Ribbon Cutting Ceremony	1st Division Road Landfill
Nov-2011	Video Clip	http://www.youtube.com
Jan-2012	News Story	http://green.blogs.nytimes.com
Jun-2012	Article	National Defense Magazine
Jan-2013	Press Release	Various
Sep-2013	Poster presentation	RETECH 2013
Various	ESTCP Fact Sheets	ESTCP Web Site and SEMs
Various	SRI Project Sheet	SRI web site and conference handouts

7.3 System Handover to Ft. Benning

Ft. Benning's stated intention is to continue operation of the FP250 so long as this can be accomplished on a revenue-neutral basis. The project participants (Southern, Ener-Core and Ft. Benning) initiated handover discussions during the fall of 2012. Operations and maintenance manuals and annual maintenance cost estimates were requested from Ener-Core and delivered to the Ft. Benning energy manager so that an operations and maintenance contract could be developed and sent out for bid.

Ener-Core submitted recommendations and costs for system updates to be completed before system handover. These include: engine overhaul, gradual oxidizer filter replacement/upgrade, and switchgear upgrades to allow for island mode operation during grid interruptions.

Although the G3 engine was installed late in the demonstration (July 2012) and accumulated less than 2000 run hours, Ener-Core determined from inspections that an overhaul of the engine is necessary to ensure reliable operation subsequent to the handover. Excess wear on the turbine nozzle and rotor was caused by particulate breakthrough resulting from the failure of the 5 micron ceramic filter solution installed in September 2012. Ener-Core has designed a solution to the filtration issue and will replace the filter with the improved version prior to resuming operations. A full history and discussion of the filtration issues is presented in section 6.1.

Because of the history of frequent grid outages at the 1st Division Road Landfill site, Ener-Core has recommended improvements to the electrical switchgear that will allow the system to operate in island mode for extended periods if necessary. The current system is able to operate in island mode for only a few minutes because grid power is necessary to run the fuel delivery compressor. This situation will be remedied with the recommended improvements. These improvements will allow the system to avoid unnecessary restarts and allow the FP250 to operate as a stand-alone energy source if desired. Ener-Core has submitted detailed design documents for the switchgear updates.

Ener-Core also plans to update the startup sequence so that only the warmer/combustor located upstream of the oxidizer is used to pre-heat the system during startup - eliminating the use of the combustor located between the turbine and the oxidizer. This change is expected to reduce turbine wear. With a single burner, the startup sequence will take about 20 hours, as opposed to 4-6 hours with the current configuration. Ener-Core will also fully automate the startup sequence. These modifications have been tested on Ener-Core's engineering development unit. These startup modifications will be completed without cost to Ft. Benning.

Formal property transfer has been completed via execution of Form DD1354 signed by Southern and the Ft. Benning real property officer (RPAO). A site walk-through was completed on May 1, 2013 by Southern and a representative of the RPAO, concluding the property transfer.

At the time of this writing, final handover arrangements depend on identifying a source for the additional funds required for the recommended system updates (totaling approximately $245k). Ft. Benning has identified an existing contract under which they will be able to provide an operator for the system and cover regular annual maintenance costs. In addition, Ft. Benning has applied for year-end funding to cover the recommended system updates and extending a natural gas line to the site. It has also been proposed that unused Phase II funds remaining in Southern's contract be used for to fund the system updates. Prior to resuming operations, Ener-Core will provide all necessary system documentation and training to Ft. Benning's operations contractor.

APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT	ORGANIZATION	Phone	Role in Project
Tim Hansen	Southern Research	919-282-1052	Principal Investigator
Bill Chatterton	Southern Research	919-282-1050	Program Manager
Eric Ringler	Southern Research	919-282-1063	Technical Lead
Paul Fukumoto	Ener-Core	949-616-3311	Director Business Development
Doug Hamrin	Ener-Core	949-616-3315	Director, Thermal Oxidizer Development
Anna Butler	USACE-Savannah District	912-652-5515	Technical Manager
Dorinda Mopeth	ACE, Fort Benning	706-545-5337	Environmental Program Manager
Vernon Duck	Fort Benning	n/a	Energy Manager (retired)
Mark Fincher	Fort Benning	706-545-0922	Energy Manager
Benny Hines	Fort Benning	706-545-4310	Public Works

Appendix B. Project Timeline

Date	Event
Sept. 2010	IR Turbine installed and commissioned at Alturdyne for acceptance testing.
Oct./Nov. 2010	Oxidizer delivered and integrated with IR turbine at Alturdyne. Begin fully integrated acceptance testing.
1/26/2011	HazOp review complete
3/25/2011	Acceptance test at Alturdyne witnessed by Southern.
4/10/2011	Start of FP250 installation at Ft. Benning.
5/20/2011	SRI monitoring instrumentation installed
6/13/2011	SRI on site to meet with Ener-Core on flare operation strategy and make minor changes to monitoring system.
7/5/2011	Start of SRI data acquisition. FP250 control wiring complete.
7/12/2011	First FP250 run. Commissioning ongoing.
7/28/2011	SRI on site to observe commissioning activities and make minor alterations to monitoring system.
7/29/2011	Hot start with resulting recuperator damage. System changes made to prevent reoccurrence.
8/15/2011	FP250 restart after recuperator replacement and repairs. Continue commissioning.
8/18/2011	SRI onsite to conduct measurements to investigate the performance of the LFG extraction system.
8/26/2011	Proposal received from SCS Engineers to assist with investigation of means to improve LFG extraction system performance to provide adequate methane concentrations for FP250 fuel delivery system.
9/21/2011	SRI/SCS conference call to review extraction system performance and plan further investigation.
9/28/2011	FP250 shut down due to site power failure. Shut down continued for inspection and maintenance. Unusual wear observed on Turbine blades.
9/29/2011	Official test start date, commissioning deemed complete by Ener-Core.
10/14/2011	FP250 restarted. Propane in use to supplement LFG supply.
10/26/2011	SRI onsite with SCS to conduct field investigation of LFG extraction system performance and repair leaks where possible.
11/8/2011	Ribbon cutting ceremony.
11/9/2011	FP250 shut down for inspection and maintenance. Root cause analysis initiated to determine source of turbine wear.
11/11/2011	Report received from SCS on results of the field investigation of LFG system performance.
1/31/2012	Turbine engine replacement completed. Root cause analysis determined that abnormal turbine wear was due to particulate breakthrough. Ener-Core proposed R&D activities to improve filtration between the filter and the oxidizer.
2/14/2012	Propane augmentation piping and controls completed.
2/15/2012	SRI on site to check sensors, observe FP250 restart activities, and inspect landfill gas extraction system. SRI's flow meter was found damaged by water that intruded during extended FP250 downtime and returned for service.
3/7/2012	FP250 restarted with 50 micron filter in place.
3/20/2012	Engine inspections completed. No unusual wear. 50 micron filter did not load up during approximately 17 days run time.

3/23/2012	Southern received draft landfill modeling report from SCS.
4/9/2012	Recuperator found partially clogged and was cleaned. Engine inspections completed. 50 micron filter determined by Ener-Core to be effective. Second propane tank installed.
4/16/2012	Final landfill modeling report received from SCS. Actual LFG recovery consistent with model results.
5/31/2012	Programming updates completed in an effort to allow the system to continue operations through a grid fault.
7/2/2012	FP250 first successfully rides out a grid fault. Over and under-voltage faults can be tolerated, but phase loss on the grid still results in FP250 shutdown.
7/23/2012	FP250 restarts with new design (G3) engine, new recuperator and improved filter design in place. Oxidizer inspected and found to be in good condition.
9/7/2012	FP250 shut down for final filter design installation. Combustor also replaced.
10/17/2012	Emissions test completed. SRI on site to facilitate and observe.
11/18/2012	Shut down due to recuperator plugging. Ener-Core decided to remain shut down until handover complete.

Appendix C: Downtime Log

DownTime (Date/Time)	UpTime (Date/Time)	Down/Up	Hours	Class	Notes
9/29/11 0:00	10/15/11 15:10	Down	399.2	RSH	Planned Outage. There was some unplanned maintenance and troubleshooting during this period.
10/15/11 15:20	10/17/11 20:00	Up	52.7	SH	
10/17/11 20:10	11/6/11 15:00	Down	474.8	RSH	Planned Outage. There may have been some unplanned maintenance and troubleshooting during this period.
11/6/11 15:10	11/9/11 13:00	Up	69.8	SH	Normal operation. Shut down due to compressor surge testing causing surge conditions.
11/9/11 13:10	2/22/12 18:20	Down	2525.2	MOH	New engine installed due to wear on turbine. Root cause analysis determined cause of wear was particulate carryover from oxidizer. Propane augmentation system installed. New filter systems in development.
2/22/12 18:30	2/23/12 13:40	Up	19.2	SH	
2/23/12 13:50	2/23/12 22:20	Down	8.5	MOH	Overloaded the data bus while programming updates were underway.
2/23/12 22:30	2/23/12 23:10	Up	0.7	SH	
2/23/12 23:20	2/27/12 23:40	Down	96.3	MOH	Reached pressure drop threshold for 75 micron filter.
2/27/12 23:50	2/28/12 15:30	Up	15.7	SH	
2/28/12 15:40	3/7/12 19:40	Down	196.0	MOH	Repaired hot spots on the oxidizer shell and piping. Made some additional programming changes, and installed the 50 micron filter for testing.
3/7/12 19:50	3/12/12 0:50	Up	101.0	SH	
3/12/12 1:00	3/12/12 23:20	Down	22.3	FOH	Propane supply for augmenting the LFG depleted.
3/12/12 23:30	3/15/12 17:10	Up	65.7	SH	
3/15/12 17:20	3/21/12 15:20	Down	142.0	FOH	Blower failure on the flare skid.
3/21/12 15:30	3/30/12 20:00	Up	220.5	SH	
3/30/12 20:10	4/9/12 18:40	Down	238.5	MOH	Shutdown due to grid fault. Remained shut down for inspection and maintenance. Recuperator clogged during previous run resulting in reduced power output.
4/9/12 18:40	4/9/12 18:50	Up	0.2	SH	
4/9/12 19:00	4/17/12 15:10	Down	188.2	FOH	Shut down due to LFG blower failure.
4/17/12 15:20	4/18/12 7:30	Up	16.2	SH	Run on LFG only (no propane augmentation)!
4/18/12 7:40	4/18/12 19:40	Down	12.0	MOH	Shutdown due to faulty interlock that closed off LFG supply.
4/18/12 19:50	4/22/12 16:40	Up	92.8	SH	

4/22/12 16:50	4/25/12 20:40	Down	75.8	FOH	Shutdown due to grid fault. Shut down extended to complete various small maintenance projects. Attempted restart on 4/23, but did not make it to oxidation mode.
4/25/12 20:50	5/4/12 20:00	Up	215.2	SH	
5/4/12 20:10	5/6/12 3:50	Down	31.7	FOH	Grid fault.
5/6/12 4:00	5/6/12 12:50	Up	8.8	SH	
5/6/12 13:00	5/7/12 16:50	Down	27.8	FOH	Grid fault.
5/7/12 17:00	5/14/12 6:50	Up	157.8	SH	
5/14/12 7:00	5/15/12 13:10	Down	30.2	FOH	Grid fault.
5/15/12 13:20	5/19/12 4:20	Up	87.0	SH	
5/19/12 4:30	5/31/12 19:10	Down	302.7	MOH	Grid fault, but remained shut down to install capability to ride out a grid fault.
5/31/12 19:20	6/3/12 9:00	Up	61.7	SH	
6/3/12 9:10	6/5/12 0:00	Down	38.8	FOH	Grid fault, or G52 breaker fault.
6/5/12 0:10	6/5/12 12:40	Up	12.5	SH	
6/5/12 12:50	6/6/12 14:40	Down	25.8	FOH	Grid fault, or G52 breaker fault.
6/6/12 14:50	6/25/12 11:30	Up	452.7	SH	
6/25/12 11:40	6/29/12 16:00	Down	100.3	FOH	Grid fault - phase outage, but remained shut down for software changes and turbine inspection.
6/29/12 16:10	7/2/12 0:10	Up	56.0	SH	
7/2/12 0:10	7/2/12 12:40	Down	12.5	FOH	Grid fault. Outage caused by electrical storm.
7/2/12 12:50	7/7/12 16:30	Up	123.7	SH	Successfully rode out a short duration grid fault during this period.
7/7/12 16:30	7/23/12 20:50	Down	388.3	POH	Replace engine with lower emissions model.
7/23/12 21:00	7/26/12 13:00	Up	64.0	SH	
7/26/12 13:00	7/27/12 17:50	Down	28.8	FOH	Grid fault. Phase outage on grid.
7/27/12 18:00	7/30/12 15:00	Up	69.0	SH	
7/30/12 15:10	7/31/12 16:30	Down	25.3	FOH	Grid fault. Phase outage on grid.
7/31/12 16:40	8/2/12 11:50	Up	43.2	SH	
8/2/12 12:00	8/3/12 21:10	Down	33.2	FOH	Grid fault. Phase outage on grid.
8/3/12 21:20	8/11/12 5:40	Up	176.3	SH	
8/11/12 5:50	8/14/12 18:10	Down	84.3	FOH	Grid fault. Phase outage on grid. Propane evaporator board failed.
8/14/12 18:20	8/20/12 0:50	Up	126.5	SH	
8/20/12 1:00	8/20/12 16:20	Down	15.3	FOH	Grid fault. Phase outage on grid.
8/20/12 16:30	8/27/12 3:20	Up	154.8	SH	
8/27/12 3:30	8/28/12 15:50	Down	36.3	FOH	Grid fault. Phase outage on grid.
8/28/12 16:00	9/3/12 17:10	Up	145.2	SH	
9/3/12 17:20	9/4/12 16:10	Down	22.8	MOH	Water in compressor lines. Engine scoped and propane vaporizer board replaced again.
9/4/12 16:20	9/7/12 14:40	Up	70.3	SH	
9/7/12 14:50	9/14/12 15:30	Down	168.7	MOH	Changed filter. During the scheduled downtime Ener-Core also upgraded the combustor used to start the FP250 and updated the insulation in that area.

9/14/12 15:30	9/22/12 11:50	Up	188.3	SH	
9/22/12 12:00	9/24/12 18:40	Down	54.7	MOH	Grid fault on an imbalanced current measured by the generator protection unit (GPU) while the turbine was transitioning to stand-by mode. There was a grid instability that caused the unit to begin switching to stand-by mode. Ener-Core believes some settings in the GPU were too tight. GPU settings relaxed to prevent ~~this~~ nuisance trips.
9/24/12 18:50	9/26/12 7:40	Up	36.8	SH	
9/26/12 7:50	9/26/12 13:30	Down	5.7	MOH	The flare valve opened due to water in the air line.
9/26/12 13:40	9/29/12 13:20	Up	71.7	SH	
9/29/12 13:30	10/6/12 18:40	Down	173.2	MOH	Ener-Core intentionally shut down the machine as the filter pressure drop had risen to a high level and they wanted to inspect and repair this issue.
10/6/12 18:50	10/8/12 2:10	Up	31.3	SH	
10/8/12 2:20	10/9/12 14:50	Down	36.5	FOH	Grid fault.
10/9/12 15:00	10/10/12 6:00	Up	15.0	SH	
10/10/12 6:10	10/10/12 19:00	Down	12.8	FOH	Grid fault.
10/10/12 19:10	10/12/12 11:10	Up	40.0	SH	
10/12/12 11:20	10/14/12 15:50	Down	52.5	FOH	Grid fault.
10/14/12 16:00	10/16/12 5:40	Up	37.7	SH	
10/16/12 5:50	10/17/12 1:00	Down	19.2	MOH	Damaged wiring due to install error during maintenance.
10/17/12 1:10	10/18/12 12:40	Up	35.5	SH	
10/18/12 12:50	10/19/12 15:50	Down	27.0	MOH	Control glitch.
10/19/12 16:00	10/29/12 2:30	Up	226.5	SH	
10/29/12 2:40	10/29/12 19:50	Down	17.2	MOH	Shut down due to a lack of propane. There is a manual ball valve connecting the second propane tank to the first that cannot be opened completely or it will overfill the first tank. This manual valve was not opened enough to supply the continuous demand of the FP, so the first tank was drained completely. Ener-Core is looking into a check valve to add to the first tank so that the manual valve can be fully opened at all times.
10/29/12 20:00	11/5/12 8:50	Up	156.8	SH	

11/5/12 8:50	11/6/12 18:20	Down	33.5	MOH	A grid event occurred and the engine surged. During the grid event the FP250 transitioned to standby but pressure compressor discharge (Pcd) and speed were both already dropping fast. Therefore, the FP250 did not successfully transition to standby and shutdown several seconds later when the BCM declared a surge fault.
11/6/12 18:30	11/9/12 6:10	Up	59.7	SH	
11/9/12 6:20	11/13/12 22:50	Down	112.5	FOH	Landfill piping failure at GV28, loose pipe at GV24.
11/13/12 23:00	11/18/12 10:00	Up	107.0	SH	
11/18/12 10:10	4/1/13 9:31	Down			The recuperator clogged and the high temperature -set point shut down the unit. Ener-Core decided to remain shut down until handover completed.

Appendix D. GHG Emissions Reduction Calculation Details

Item	Quantity	Units	Information Source	Notes
FP250 net generating capacity	220.1	kW	Demonstration data for G3 engine in flex mode operation.	Average net power including startup periods is 215.2 kW.
FP250 efficiency	14994	Btu/kWh	Demonstration data for G3 engine.	
FP250 availability	90%	%	Specification from Ener-Core	Actual availability during demo was lower. See section 5.2.6.
Seasonal de-rating factor	100%	%	Demonstration data.	Average net power output for G3 operating period was verified as representative of expected annual output via curve fit to demonstration data and using the curve to model expected output at average temperature in each month of the year using RETscreen climate data for Columbus, GA.
Percentage of power generated from LFG	82%	%	Demonstration data.	For 2012. Supplemental fuel usage will increase in out years as LFG supply diminishes.
Gross capacity factor	90%	%	Calculation	Accounts for availability and seasonal de-rating.
Gross capacity factor with partial generation from propane	74%	%	Calculation	Accounts for availability, seasonal derating, and supplementary propane.
FP250 parasitic load factor	100%	%	Demonstration data.	There is no parasitic load factor as figures are based on net power generation.
Net capacity factor	90.0%	%	Calculation	Gross capacity factor less parasitic load factor.
Local utility electric generation CO2e emission factor	1.2927	lbs CO2/kWh	eGRID 2012 v1.0 Georgia State annual CO2 equivalent total output emission rate (lb/MWh). Data are current 2009.	
Heat content of methane	1012	Btu/scf	Standard reference.	Higher Heating Value (HHV)
FP250 Avoided emissions reduction (due to power generation)	1018	metric tons CO2e/yr	Based on EPA LMOP LFGE benefits calculator formula.	Uses net capacity factor.
Direct emissions reduction due to CH4 destruction: FP250 or flare	8495	metric tons CO2e/yr	Based on EPA LMOP LFGE benefits calculator formula.	Uses gross capacity factor de-rated to account for supplementary propane use. LMOP model assumes all CH4 is destroyed.

Flare CH4 destruction efficiency	98.0%	%	NSPS requirement for NMOC DRE and design value for open flares.	Ft. Benning flare may be less efficient due to low heating value of LFG.
FP250 CH4 destruction efficiency	99.6%	%	NMOC destruction efficiency from 10/17/12 emissions test	
Direct emissions reduction (due to CH4 destruction): Flare	8325	metric tons CO2e/yr	Calculation	Accounting for destruction efficiency
Direct Emissions Reduction (due to CH4 destruction): FP250	8461	metric tons CO2e/yr	Calculation	Accounting for destruction efficiency
Additional CH4 reduction due to greater FP250 destruction efficiency compared to flare	136	metric tons CO2e/yr	Calculation	
Flare pilot fuel use (propane) - without FP250	20179	lb/yr	Using 50k Btu/hr flare fuel consumption based on Flaregas specifications.	Assumes 24/7/365 flare pilot operation.
Flare pilot fuel use (propane) - with FP250	2017.9	lb/yr	Calculation	Assumes 90% FP250 availability and flare does not run when FP250 runs.
Propane combustion CO2 emissions factor	2.96	lb CO2/lb propane	AP42 - Table 1.5-1. EMISSION FACTORS FOR LPG COMBUSTION	12.5 lb CO2/gallon propane. 1 gallon propane = 4.23 lb.
CO2 emissions due to flare pilot fuel use - flare alone	32.9	metric tons CO2e/yr	Calculation	
CO2 emissions due to flare pilot fuel use - with FP250	3.29	metric tons CO2e/yr	Calculation	Assumes 90% FP250 availability and flare does not run when FP250 runs.
Additional GHG reduction due to flare pilot fuel savings	29.6	metric tons CO2e/yr	Calculation	
Typical number of startups per year	6		FP250 Power O&M Specification	
Gallons propane per start	115	gallons	Demonstration data.	Average over approximately 30 starts.
Annual startup propane usage	690	gallons	Calculation	
Annual augmentation propane usage	59,771	gallons	Demonstration data.	Annualized (assuming 90% availability). Will increase as LFG supply diminishes.

Total annual propane usage	60,461	gallons	Calculation	For FP250 startup and augmentation (at 2012 augmentation rate)
Total annual propane usage	255,145	lbs	Calculation	For FP250 startup and augmentation (at 2012 augmentation rate)
Annual CO2 emissions due to propane usage	755,230	lbs	Calculation	For FP250 startup and augmentation (at 2012 augmentation rate)
Annual gross FP250 CO2 emissions due to propane usage	416	metric tons CO2e/yr	Calculation	For FP250 startup and augmentation (at 2012 augmentation rate)
Annual net FP250 CO2 emissions due to propane usage	387	metric tons CO2e/yr	Calculation	For FP250 startup and augmentation (at 2012 augmentation rate) less GHG reduction due to flare pilot fuel savings.

Appendix E: References

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Appendix F: Ener-Core Comments

This section was prepared by Ener-Core, and is directed primarily at economics of the FP250 technology.

Positive Economic Impact of Ener-Core Potential Cost and O&M Reduction

The economic performance of the FP250 was based on current 2013 equipment, operation and maintenance pricing. As the FP250 is a new product, it has not yet benefited from the cost-reductions that may be achieved from engineering/manufacturing cost reductions, and economies of scale in manufacturing. In addition, as the product goes through a normal maturation process, the Operations and Maintenance (O&M) costs may also be reduced. Ener-Core believes a cost reduction of 20% for both the product cost and O&M may be achieved.

From section 5.3.7, the levelized cost of energy (LCOE) for an energy generating technology is the energy price at which the NPV of the life cycle cost of the technology over the equipment lifetime is zero. The energy price must reach the LCOE value for the project to break even and exceed the LCOE value for the technology application to produce a positive net savings or return on investment. The LCOE thus provides a common basis for comparing the cost of competing energy technologies and assessing the cost competiveness of a given technology.

With the assumed 20% reductions, an FP250 20 year project achieves a positive return on investment at an electricity price of $0.079/kWh. Referenced from section 5.3.4, commercial sector electric prices (as of December 2012) are at $0.0982/kWh nationwide and $0.0923/kWh in Georgia.

Georgia Power's Green Energy Program sells renewable energy at a premium of $35/MWh ($0.035/kWh) for standard green energy and $50/MWh for premium green energy (must include at least 50% solar). Georgia Power supports distributed generation and maintains a program to purchase renewable and non-renewable energy at their avoided energy cost. In 2012, Georgia Power's avoided energy costs were $123.26/MWh (peak) $75.12/MWh (peak season/off peak hours) or $74.16 (off peak) [20].

The electrical output of the FP250 (~250 kW) best fits into the commercial rather than industrial electricity category. Figure1 compares the FP250 LCOE current and reduced pricing to the fossil fuel commercial rates nationwide and in Georgia. With these electricity rates and the reduced FP250 costs it can make economic sense to install and operate the system.

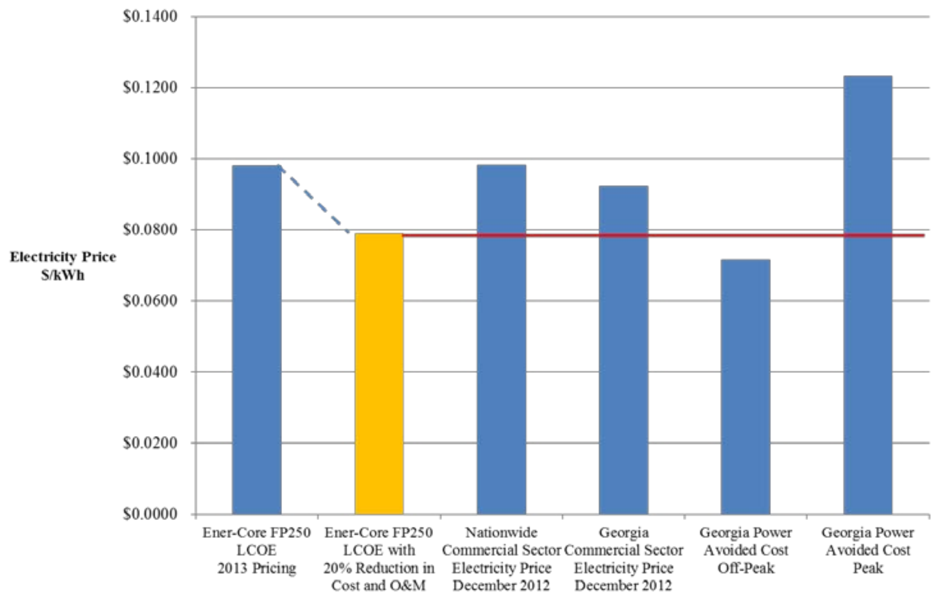

Figure 1. FP250 LCOE Comparison to U.S. Average and Georgia Electricity Prices $/kWh

Comparison to Photovoltaic Solar for Ft. Benning Renewable Energy Generation

The LCOE of the FP250 for current pricing and 20% improved cost is compared to photovoltaic solar renewable generation technology. Figure 2 presents this comparison. Based on the NREL Open database [24], the calculated LCOE of the FP250 is lower than the LCOE data for photovoltaic solar.

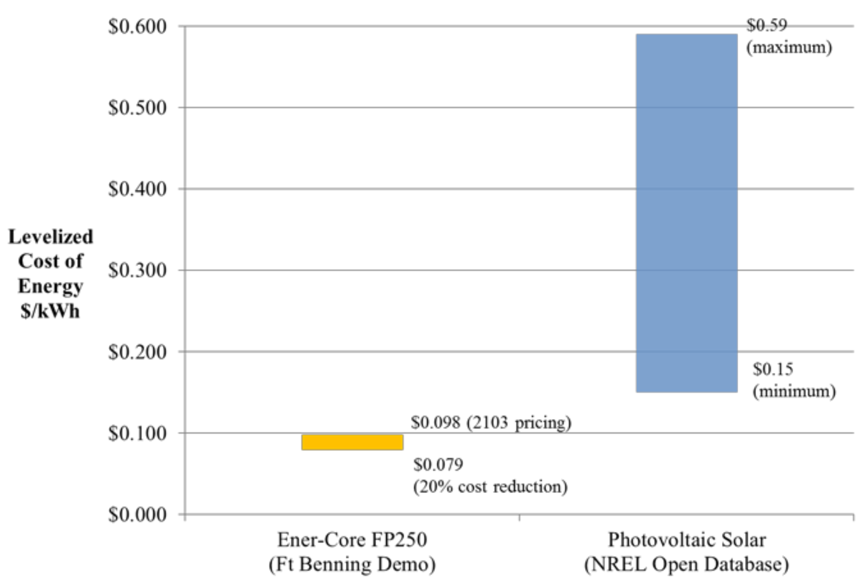

Figure 2. FP250 LCOE Compared to Photovoltaic Solar

The capacity of the FP250 for the demonstration project is compared to photovoltaic solar, another onsite renewable generation technology (Technology availability is equivalent to capacity factor). Figure 3 presents this comparison. Based on the NREL Open database [24], the capacity factors for the FP250 as demonstrated at Fort Benning and estimated on planned site/equipment upgrades are significantly higher than photovoltaic solar capacity factor range in the NREL Open Database.

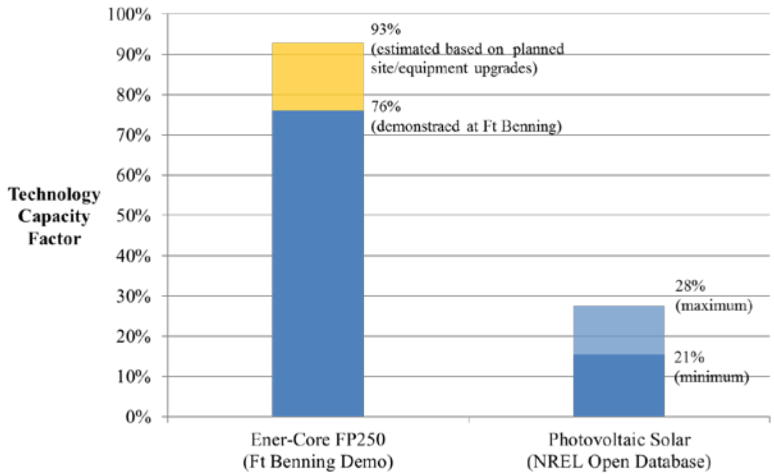

Figure 3. Renewable Generation Capacity Factor Comparison: FP250 Versus Photovoltaic Solar

Economics of FP250 Summary

The economic analysis shows that the FP250 can be a viable renewable energy solution. The FP250 produces more renewable electricity (kWh's per year) at a lower LCOE than photovoltaic solar.

With assumed 20% product cost reductions, the LCOE of the FP250 on a renewable fuel is nearly 20% below the average commercial electricity rate nationwide. In addition to the renewable energy attributes, the FP250 with assumed cost reductions could offer electricity competitive with non-renewable electricity rates. This does not include benefits from federal or state subsidies.

Acknowledgement

Ener-Core strongly values its relationships with Southern and the DoD and thanks both for their support throughout the Fort Benning demonstration. The Fort Benning project provided Ener-Core with an opportunity to operate the FP250 on a closed landfill with application challenges. In addition to overcoming the application challenges outlined in this report, we also made key improvements to core components, such as the filter, insulation systems, and system controls. These changes and improvements will be included in future applications and the commercial product. We intend to continue to make minor modifications to the FP250 to improve its reliability and operability.

Ener-Core believes that Gradual Oxidation provides a unique value proposition, both for the DoD and our wider customer base. Only our products and technology allow for the extraction of energy from previously unusable low Btu fuels, while significantly reducing harmful pollutants and creating useful energy products such as heat and electricity.

We believe our products and technologies can unlock power generation for a wide range of low-quality fuels that extend beyond traditional gas turbine and reciprocating engine operating limits, and we currently expect to scale up our technology to be integrated with a variety of larger turbines for power generation, providing an alternative to typical combustion-based generation. We believe that the DoD and our other customers can greatly reduce the cost of compliance with air quality regulations by avoiding the chemicals, catalysts, and complex permitting required by competitive systems.

Finally, we hope to work with Southern and DoD to ensure that the recommended FP250 updates at Ft. Benning are completed and the system continues to produce renewable energy in the years to come. We appreciated our continued partnership.